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FINAL REPORT

STUDY OF FIBER OPTICS STANDARDIZATION,
RELIABILITY, AND APPLICATION

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STUDY OF FIBER OPTICS STANDARDIZATION, RELIABILITY, AND APPLICATION

S. P. Sauve - Program Manager

O. R. Mulkey - Technical Leader

R. F. Braun - Technical Contributor

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1.0 INTRODUCTION

This report represents the work performed under the NASA/George C. Marshall Space Flight Center Contract NAS8-33564 entitled "Study of Fiber Optics Standardization, Reliability, and Application." The objectives of this study were to:

1) Determine the current status of the fiber optic standardization effort and identify the time frame for implementation of realistic standards.

2) Determine the prime components for which standardization can be implemented.

3) Detail testing problems, field reliability problems, and optimum application areas for space equipments.

The technical approach used to identify the maturity of fiber optic components and to determine current/future standardization activity was conducted by a survey of both industry and government users and suppliers of fiber optic components and systems. The results of this survey were then analyzed to determine the maturity of fiber optic components, standardization efforts, test problems, and potential NASA applications. The overall program approach is shown in Figure 1.1.

Out of approximately 80 companies involved in various aspects of fiber optics that were identified in the initial phase of this program, 49 were selected as having sufficient background/information relative to this contract. All 49 companies, both manufacturers and users of fiber optic components, were sent survey forms. Twenty-seven (27) of these firms chose to complete the survey with the requested information. Out of these companies, as well as selected companies that did not respond and various government agencies, 26 were selected for an in-plant visit. As a result of the surveys and the subsequent visits and follow-up technical discussions, sufficient information/data was obtained to draw conclusions pertinent to fiber optic standardization, reliability, and application.

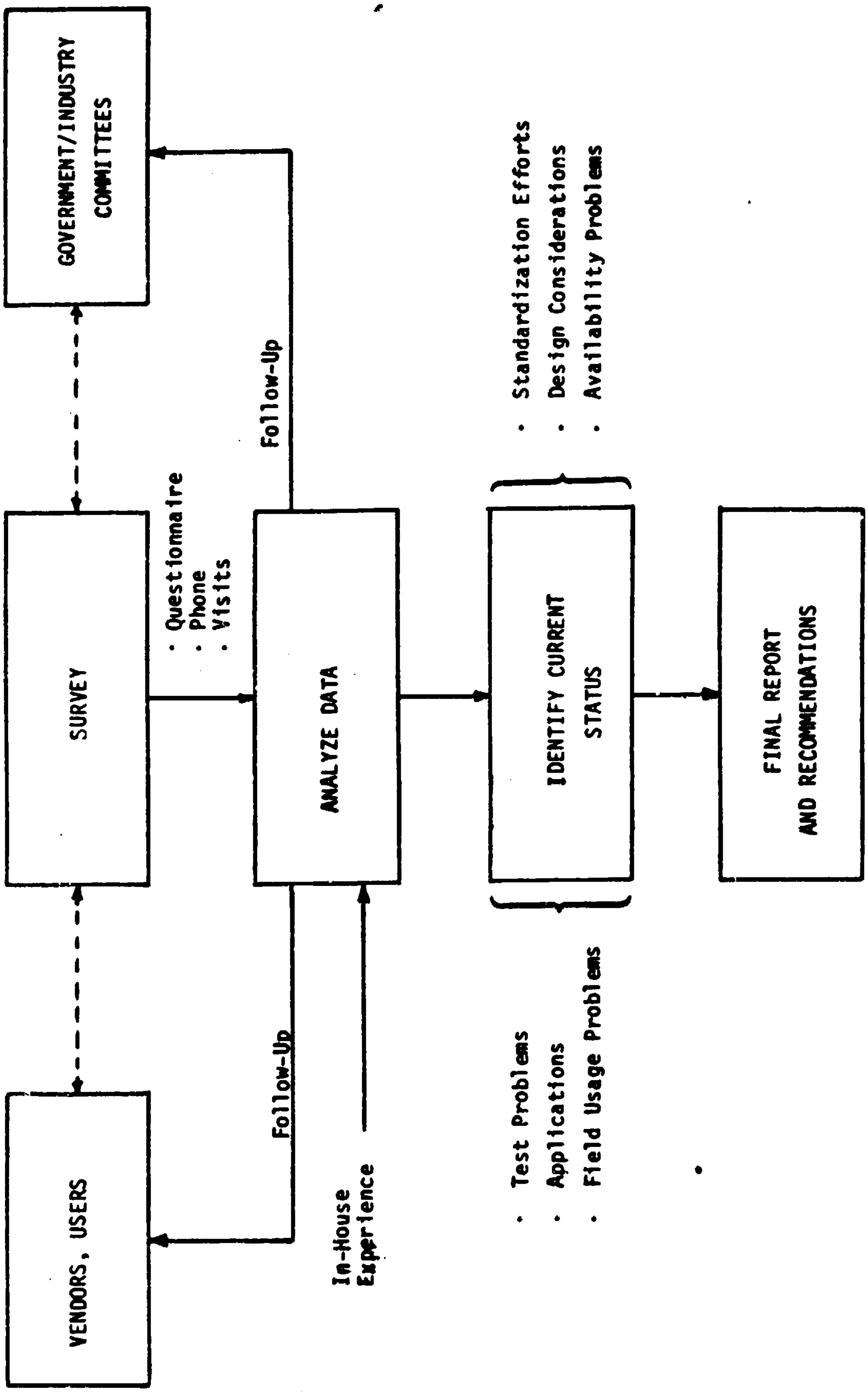


FIGURE 1-1: OVERALL PROGRAM APPROACH

Section 2.0 summarizes the significant findings of the program. Section 3.0 describes the actual data search program and details the findings at each of the companies/agencies that were visited during this study. Analysis of the data/information gathered during this study is presented in Section 4.0. Section 5.0 details the detailed conclusions to be drawn from the analysis and Section 6.0 lists the bibliography.

This report also has an appendix that contains samples of the survey forms that were mailed to fiber optic component manufacturers and users.

With the publication of this document, the objectives of this program have been successfully completed.

2.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

2.1 Summary and Conclusions

As a result of the data collection and analysis effort, several key conclusions can be drawn relative to the use of fiber optics in space applications. Although most of the manufacturers and users detailed the problems they were having with the use of or manufacture of fiber optic components, the general consensus of all the companies/agencies interviewed is that fiber optics is a maturing technology and will definitely have a place in future NASA system designs. The reasons for this are complex and varied but basically reduce to two main advantages - weight savings and increased bandwidth.

Table 2-1 describes the weight and bandwidth advantages. As can be seen, the weight savings is dependent upon the type of standard electrical cable to which it is being compared. As compared to twisted pair (22 gauge), fiber optic cables offer approximately 22% savings in weight. For coax cable (higher data rate information), the savings is over 90%.

In a recent contract performed for Naval Ocean Systems Center (Reference 12), a fiber optic cable was built to replace an existing standard electrical cable. The fiber optic cable utilized both fiber optics (for signal lines) and standard electrical wire (for power). After construction of the fiber optic cable, it weighed 50% less than the comparable electrical cable. Although the weight savings will vary depending upon cable configuration, data rate, wire type, and complexity, a weight saving of at least 20% is obtainable. The FOCAP study (Reference 16) also showed significant savings in weight and cost. Especially in systems operating at over 1 megabit/second.

Table 2-1 also addresses bandwidth, again as compared to twisted pair and coax. At a standard loss of 4 db/KM, the fiber optic cable (single strand graded index glass fiber) can operate up to 1 GHz. By comparison, both twisted pair and coax can operate only below 1 MHz. In this case, there are over ten orders of magnitude increase in bandwidth capability of a fiber optic cable as compared to twisted pair/coax.

WEIGHT COMPARISON

CABLE TYPE	WEIGHT
OPTICAL (SINGLE STRAND GRADED INDEX)	22.8 KG/KM
TWISTED WIRE PAIR (22 GAUGE)	28.8 KG/KM
COAX (RG-58/U)	43.5 KG/KM

BANDWIDTH COMPARISON

CABLE TYPE	BANDWIDTH (AT 4DB/KM LOSS)
OPTICAL (SINGLE STRAND GRADED INDEX)	1 GHz
TWISTED PAIR (22 GAUGE)	150 KHz
COAX (RG-58/U)	180 KHz

TABLE 2.1 COMPARISON OF FIBER OPTIC CABLES WITH ELECTRICAL CABLE

At the present time, specific benefits for fiber optics are hard to quantitize. This is true because the specific saving is dependent upon many factors such as frequency, line length, radiation requirements, cable configuration, system complexity, reliability requirements, and performance requirements. For NASA systems, however, the primary benefits will be weight savings, increased bandwidth, increased EMI/EMP immunity, elimination of ground problems and, ultimately, cost.

The manufacturers and users interviewed during the survey generally expressed the opinion that fiber optic technology can be used today in space applications - if they are used with the proper design guides. Most devices have their own unique strengths and weaknesses. If each device (source, detector, fiber/cable, and coupler) is picked carefully, keeping in mind the strengths/weaknesses as compared to the other components in the design, then an adequate system for space use can be built. However, this sytstem will not be optimized in terms of performance, reliability, and cost at this time.

Optimization will occur when standard devices are available. Both users and manufacturers stated the need for standard components. These components would simplify the device selection criteria, reduce cost, and optimize system performance. Standards exist today only in the form of one test standard for cables and an industry standard glossary. Standards for all major fiber optic components are feasible and are now in various stages of development, mainly through the EIA P.6 committees (see Table 2.2). Generic specifications should be available by the end of 1980. Detail specifications on particular components are not yet in work but will be started in 1980 and sources, detectors, fiber will be available at the end of 1980.

Standard components for military requirements are in development and should be available in at least two years (for all components). If NASA can utilize the military requirements, then standard candidates for space applications will be available at this time. If NASA requires their own unique set of system/device requirements to which standard parts must be developed, then these standard components are at least 3 to 4 years away.

COMPONENT	PRIORITY	STATUS	PRIME COMMITTEES	WORK TO BE DONE
FIBERS/CABLES	1	TEST METHODS OUT FIBER SIZES SELECTED	SAE A2H EIA P6.6 P6.7	UPDATE TEST METHODS (DoD 1678) DEVELOP GENERIC SPEC
CONNECTORS	1	TEST METHODS IN WORK GENERIC SPEC NEAR COMPLETION	EIA P6.3	RELEASE TEST METHODS RELEASE GENERIC SPEC DEVELOP DETAIL SPECS
SOURCES	1	GENERIC SPECS FORMAT DEFINED	EIA P6.5	DEVELOP GENERIC SPECS DEVELOP DETAIL SPECS DEVELOP TEST METHODS
DETECTORS	1	GENERIC SPECS FORMAT DEFINED	EIA P6.5	DEVELOP GENERIC SPECS DEVELOP DETAIL SPECS DEVELOP TEST METHODS
COUPLERS	2	NO ACTION	EIA P6.3	DEVELOP GENERIC SPEC DEVELOP DETAIL SPECS DEVELOP TEST METHODS
MODULES	2	NO ACTION	EIA P6.5	DEVELOP GENERIC SPEC DEVELOP DETAIL SPECS DEVELOP TEST METHODS

TABLE 2.2 STANDARDIZATION CATEGORIES

NOTE: REFER TO SECTION 5.2 FOR FURTHER DETAILS

Applications for fiber optics in NASA systems include both long haul and short haul data transfer links. The low loss, light weight, and high bandwidth of fiber optics offer a particular advantage for space applications. The implementation of fiber optics in new systems will depend upon the importance of the benefits of fiber optics compared to some of the disadvantages which include interconnect problems, lack of standards and lack of reliability data. Use of fiber optics in both government and industrial long haul applications have proven to be cost effective in these types of applications. The rapid development of new components shows promise for cost effective use in space applications in the very near future.

A summary of the manufacturer and user comments is given in Tables 2.3 and 2.4 respectively. Again, the basic conclusion of the results of this survey is that there is a class of fiber optic components available today that can, if used properly and with competent system design, be used in space applications.

This is not to say that further development in the area of components, testing, standardization, reliability, and application is unnecessary. Developmental work in all areas is needed. Specific conclusions of each device type/category pertaining to fiber optic technology for space use are listed below.

- Detectors - Devices are available which will meet the requirements of airborne, ground, and space applications. The devices are not optimized in that packaging does not provide high coupling efficiency and hermeticity. These problems are being worked by several manufacturers. Reliability is expected to be that of conventional silicon diodes.

- Sources - Fiber optic sources are available that can satisfy selected space applications. The major developmental area in the future will be packaging - hermetic devices and the elimination of epoxies. Reliability figures are not available but, if conservative design criteria are used, these devices can meet most space requirements. It is recommended that all parts be burned in before use. Critical design parameters, with respect to performance, are temperature effects on power output levels and extreme sensitivity to electrical overstress.

- TECHNOLOGY IS AVAILABLE TO SUPPLY COMPONENTS TO MOST REQUIREMENTS (SEE SECTION 5.1.1)
- COSTS ARE GOING DOWN BECAUSE USAGE IS GOING UP AND PRODUCIBILITY IS IMPROVING. SOURCES AND CABLES WILL DROP TO 10% OF CURRENT COSTS. TIME FRAME OF REDUCTIONS IS USAGE DEPENDENT.
- LACK OF STANDARDS IS HURTING IMPLEMENTATION
- TELECOMMUNICATIONS IS THE PRODUCT DRIVER TODAY
- LIMITED DATA EXISTS TO PREDICT RELIABILITY

TABLE 2.3 SUMMARY OF MANUFACTURER'S COMMENTS

- TECHNOLOGY IS MATURING AND WILL SEE RAPID GROWTH OVER THE NEXT DECADE
- ADVANTAGES (WEIGHT-BANDWIDTH PRIMARILY) DICTATE THAT FUTURE SPACE PLATFORMS WILL HAVE FIBER OPTICS
- COMPONENTS NOT OPTIMUM BUT USABLE
- LACK OF STANDARDS IS HURTING IMPLEMENTATION
- INCONCLUSIVE RELIABILITY DATA
- BECAUSE OF NONAVAILABILITY OF COMPONENTS TO MEET SPECIFIC REQUIREMENTS, SEVERAL USERS FABRICATE THEIR OWN

  CONNECTORS,
  TEST EQUIPMENT,
  AND ILD'S
- COST NOT A SIGNIFICANT FACTOR EXCEPT FOR HIGH PERFORMANCE SOURCES & CONNECTORS
- COUPLERS - NOT HERE YET

TABLE 2-4 SUMMARY OF USERS COMMENTS

- o Connectors - Generally, connectors are not developed far enough for full space use over a wide variety of applications. Although specialized connectors can be procured (or modified from commercial connectors) to meet specific applications, the overall development of hermetic, right-angle, and multipin (to accept various fiber types as well as electrical wire) connectors has not been fully addressed. Many different types of connectors are now available, clouding selection of the proper component. Each company is using a different method of alignment and fiber confinement. Most have overlooked other considerations such as strain relief and fiber interface protection. Standards for connectors are fairly far along and will be out early in 1980. The choice of connectors must be closely coordinated with that of the cable system used. This cannot be overemphasized.

- o Cables - Plastic clad silica (PCS) fibers are most suitable for space applications, but low temperature operation (below -20°C) is still a major problem. Total dose radiation damage testing indicates that PCS fibers are least affected by radiation effects, but all test results are not in and the issue is still clouded. New methods of termination for PCS and changes in construction to allow full temperature operation (-55°C to +125°C) are in development.

- o Other Components - Couplers, transmitter modules, and receiver modules developed to date appear to be primarily for ground site applications. No detailed standards are in process for this class of component to date. These standards will follow after the more pressing ones are in work (i.e., fibers/cables, sources, and detectors).

- o Reliability - Reliability data to date has been inconclusive and consists mainly of user reports and limited device testing by manufacturers. Of the basic 4 types of components, enough data exists to form estimates for only detectors and sources. A conservative estimate of the failure rate for detectors is .17%/1000 Hrs, while for sources, the rate is 1%/1000 Hrs. Insufficient data exists to form an estimate of the reliability of cables and connectors.

- Test - Test methods for cable and connectors have been developed and the former has been released. The equipment needed to perform some of the optical measurements is mostly lab type and is not suitable for production or field use. Methods for active devices are further behind in that test methods are not yet in development by industry standards committees.

- Standardization - Planning for the development of nearly all required specifications and standards has been completed and the documentation is in the developmental stage. Only cable test standards have been released. Government and industry are working together primarily through the tri-services committee, the EIA, and SAE.

- Applications - Present applications are primarily telecommunications and computer data link oriented but space applications are feasible and suitable systems can be designed using present state-of-the-art components. These systems won't be optimum but they will satisfy most requirements.

2.2 Recommendations

To proceed further with the standardization efforts and implementation of Fiber Optics into advance NASA systems, the following recommendations are made:

- NASA should become involved with the various committees working on standardization, especially the EIA/SAE committees. This would ensure the consideration of NASA requirements as well as keep NASA informed of the progress of standardization.

- Fiber optic designs be selected for noncritical applications. Ground as well as space platform applications should be considered. This will result in operational experience for future widespread use of fiber optics.

- A series of basline components, suitable for a variety of applications, need to be selected. Concentrating on only a few components will allow more direct contact with the manufacturers. Reliability information and component improvements will be more easily obtained this way.

- Support documentation and procedures should be developed. Test criteria and screening requirements will be established. Design guides to ease implementation are to be developed. Field maintenance procedures will be developed in order to facilitate repair and improve reliability of installed systems.

3.0 DATA SEARCH AND CONTACT

The purpose of this program is to identify the maturity of fiber optic components, determine current/future standardization activity that will result in identification of reliable standard components for fiber optics and identify optimum application areas for fiber optic designs to be utilized in NASA space applications.

It was felt that the best way to obtain the necessary data was to seek out and interview the experts in this field. The wide spectrum of people interviewed ensured a background of sufficient depth upon which to base our findings.

In order to identify the people with the most pertinent data required several steps. The first step was an exhaustive literature search to identify potential vendors, users, and committees involved in fiber optics. See Table 3.0. A list of technical papers and articles that were reviewed during this program is presented in the bibliography. From this review, a significant number of sources were identified who appeared to have data or meaningful information on fiber optics technology.

To best determine current/future fiber optic standardization, reliability, and application information, survey questionnaires were prepared and mailed to 49 manufacturers and users. Two separate surveys, as shown in Appendix A, were sent to the two main areas of fiber optic components concern: manufacturers/suppliers and users. The purpose of this survey was twofold. First, it was designed to identify specific areas that companies were involved in fiber optics, contacts at the particular company, and a willingness for the company to share information. Secondly, the survey tried, in general terms, to identify test, application, and reliability problems as well as standardization efforts.

From past experience on other survey programs and due, in part, to the contract duration of this program, the survey did not seek out detailed information. It was felt that the more specifics requested in the survey would lessen the

USERS

BELL LABS
BOEING
CENTRAL TELEPHONE
GTE
HUGHES
LOCKHEED
MARTIN MARIETTA
McDONNELL-DOUGLAS
NORTHRUP
ROCKWELL
TELEPROMPTER
UNITED TECHNOLOGIES

DoD AGENCIES

AFAL
AFWL
ERADCOM
NAC
NASC
NOSC
NUSC
RADC

MANUFACTURERS

AEG TELEFUNKEN
AMP
AMPHENOL
AUGUT
BELDON
BENDIX
BERG ELECTRONICS
BURNDY
BURR-BROWN

MANUFACTURERS CONT'D

CABLEWAVE
CANOGA DATA SYSTEMS
CANSTAR COMMUNICATIONS
CENTRONIC
CORNING
DEUTSCH
DEVAR
DUPONT
EG&G
FIBERGUIDE INSTRUMENTS
FIBEROPTIC CABLE
FORT
GALITE
GENERAL CABLE
GENERAL ELECTRIC
GENERAL OPTRONICS
HARRIS
HEWLETT PACKARD
HITACHI
HUGHES
INTRADE
ITT
LASER DIODE LABS
MAXLIGHT
MERET
MITSUBISHI ELECTRIC
MOTOROLA
NATIONAL SEMI CONDUCTOR
NEC
OIS
OPTIXX
ORIONICS
PHOTODYNE
PLESSEY
QUANTROD

TABLE 3.0 ORGANIZATIONS INVOLVED IN FIBER OPTICS

MANUFACTURERS CONT'D

QUARTZ PRODUCTS
RADIATION DEVICES
RCA
ROFIN
SEALECTRO
SIECOR
SILICON DETECTOR
SPECTRONICS
SPERRY
STANDARD TELEPHONES &
CABLE LIMITED
SUMITOMO ELECTRIC IND.
TEXAS INSTRUMENTS
THOMAS & BETTES
3 M
TIMES FIBER
TROMPETER ELECTRONICS
TRW
UNITED DETECTOR TECHNOLOGY
VALTEC

TABLE 3.0 ORGANIZATIONS INVOLVED IN FIBER OPTICS likelihood of getting the survey filled out and returned. The survey questionnaire was geared to be efficient in terms of time necessary to fill it out and effective in determining general information on fiber optic technology.

To obtain the necessary specific information, all respondents to the survey questionnaire (27 out of 49 - 55%) were contacted by telephone. These companies that indicated a willingness to share technical information on their products and/or use of specific products were selected for an in-plant visit. In addition, all companies that did not respond were also contacted. Out of these companies, several were identified that had data to share but would not fill out the survey. They believed that filling out a survey form would potentially divulge proprietary information and, therefore (even with assurances to protect proprietary information), would not fill out the questionnaire.

Besides the manufacturers/suppliers and users, all major DoD agencies involved with fiber optic application and standardization were contacted for information on their specific activities.

In total, out of the over 80 firms contacted, 26 were selected for an in-plant visit. A list of the companies/agencies visited is given in Table 3.1. These companies represent a good cross section of active manufacturers and users of fiber optic components as well as selected government agencies involved with the standardization and specification of these devices. What follows is the detailed information obtained from each visit.

3.1 Company A

Company A is a large manufacturer of semiconductor devices. They are producing diodes (both sources and detectors) suitable for fiber optic use as well as complete fiber optic transmitter and receiver modules.

TABLE 3.1 COMPANIES INTERVIEWED

Air Force Avionics Laboratory
Wright-Patterson Air Force Base
Dayton, OH

Air Force Weapons Lab
Kirtland Air Force Base
Albuquerque, NM

Amp
449 Eisenhower Blvd.
Harrisburg, PA 17105

Amphenol/Bunker Ramo Corp.
33 E. Franklin St.
Danbury, CT 06810

Canoga Data Systems
6740 Eaton Ave.
Canoga Park, CA 91303

Deutsch
Banning, CA 92220

Exxon Enterprises Inc.
350 Executive Blvd.
Elmsford, NY 10523

Galite, Inc.
Wallingford, CT

General Optronics
3005 Hadley Rd.
S. Plainfield, NJ 07080

GTE Lenkurt
1105 County Rd.
San Carlos, CA 94070

Hewlett Packard
Optoelectronics Division
640 Page Mill Rd.
Palo Alto, CA 94304

Laser Diode Labs
1130 Somerset St.
New Brunswick, NJ 08901

Lockheed Advanced Systems Division
Palo Alto, CA

Martin Marietta, Denver Division
Watertown, CO

Maxlight Optical Waveguides
Box 11288
Phoenix, AZ 85061

McDonnell Douglas Austronautics Co.
St. Louis, MO

MERET Inc.
1815 24th St.
Santa Monica, CA 90404

Motorola Semiconductor
P.O. Box 2953
Phoenix, AZ 85062

Naval Underwater Systems Center
New London, CT

Orionics Inc.
5901 Gibson Blvd. SE
Albuquerque, NM 87108

Photodyne Inc.
5356 Sterling Center Dr.
Westlake Village, CA 91361

Spectronics
830 E. Arapaho Rd.
Richardson, TX 85080

Texas Instruments
Box 225012, MS 308
Dallas, TX 75265

Times Fiber Communications
358 Hall Ave.
Wallingford, CT 06492

Trompeter Electronics
8936 Comanche Ave.
Chatsworth, CA 91311

Valtec Corp.
99 Hartwell St.
West Boylston, MA 01583

The discussion with Company A was primarily concerned with their fiber optic transmitter/receiver modules. They plan to push the modules now and discrete components in the future. A high degree of quality assurance and inspection is used in the production of the components and modules. Reliability problems have been virtually nonexistent. A percentage of each batch of modules produced is used for life tests.

The main limitation of their modules, they feel, is the packaging. The epoxies used are only reliable between 0°C to 70°C. Also, as the fiber pigtail/connector is mounted in epoxy, a true hermetic seal is not achieved. Instead, the seal is referred to as pseudo hermetic and is tested per MIL-STD-106 between -7°C to 65°C at 95% humidity (for a hundred cycles). It was felt that the temperature limitations would be easier to solve than the hermeticity problem.

The actual active fiber optic components (LED, PIN diodes) are electrically isolated due to the ICs incorporated in the modules. The modules can be treated as any other TTL type device. Failure modes of the modules can be separated into two categories: mechanical/environmental and electrical. The mechanical/environmental problems are centered on the fiber interface and appear to be mainly adhesives related. The LED is also susceptible to mechanical/environmental limitations such as temperature and humidity. The PIN diode in the receiver module is very rugged. Some failures have been observed in the tantalum capacitors incorporated in the receiver circuit, however.

A new transmitter module incorporating a recently developed Burrus LED will shortly be announced. This will extend the transmission capability of the modules from their current 100m length out to 1000m. The Burrus diode has been three years in development. Made of GaAlAs, it has a wavelength centering around 820 nm. The most extraordinary characteristic of the diode is that there is no indication of degradation with time. As all previous LEDs have exhibited a gradual degradation with time, this seems questionable. However, Company A stated they have data (soon to be released) to back up their claims. The estimated MTBF is in the neighborhood of 1.5×10^6 hours. Radiation hardness testing is now being started on the modules and components but it will be a few months yet before they have any results.

Application limitations are primarily environmental (aside from length of links). The epoxies used are limited to 0° to 70°C and the humidity range is similar to other epoxy ICs. Cleanliness at the installations can be a problem as dirt will seriously impair the performance of the connectors. To date, the modules have been used in specialty-type installations and not in a production basis. In January, 1980, field installation products as well as field maintenance information will be released. It was felt that the main impact of the lack of standards has been to delay the implementation of fiber optics on a wider basis. There is no second sourcing (yet).

Testing has also been affected by the lack of standards. All test equipment has been in-house built. The light measurement is NBS traceable. Optical measurements are a problem while electrical measurements are standard.

The company indicated they had no hard plans to develop a mil/space qualifiable fiber optic module.

3.2 Company B

Company B is a large aerospace company with much experience in both systems management and in spacecraft operation and development. The company feels that present hardware can be utilized effectively in space but standards need to be developed and parts should be qualified.

The fiber optic activity here is primarily spacecraft oriented. The group has recently completed a feasibility study for a major DoD laboratory. The major outputs of this program were a series of reports which documented system concepts, preliminary design, parts selection, and selection criteria and radiation effects on fiber optic components. The group is currently under contract to develop high rate data buses for spacecraft applications.

They believe lack of space qualified hardware is of prime concern. It is their opinion that many devices presently on the market, detectors and sources particularly, are suitable for space use but that no specifications are available or tests performed to prove this. Cable and connectors are usable but much more data needs to be gathered in the way of radiation resistance for fibers. Connectors are certainly not optimized for space applications.

One of the prime concerns in the active devices is lack of hermeticity in any of the presently available packaging schemes being used. They are aware of the work going on in this area, however. The injection laser is the most favored source for the applications they have in mind which are primarily data buses. They feel that their frequency response, efficiency, and power output are their prime virtues but are also concerned with the problems in hermeticity, temperature dependence, and reliability. They are presently evaluating a group of 22 devices as part of a contract and feel fairly happy with this product. When asked about the present state of the art on couplers, they thought that they were not suitable (or available), all the technology needed to produce a satisfactory product is available today. The star coupler, of course, was the type most favored by them for the data bus applications.

The type of fiber they feel is most suitable is plastic clad silica, core size from 100-200μ. They feel that silica core, doped glass clad fibers also have potential but again that more data with respect to radiation and other effects is needed. They feel that fibers should be of as low a cross section as possible to reduce radiation effects and therefore see no potential for any fiber bundle type technology. The primary type of space satellite concerned with at this facility was the surveillance type which contains at least 2 fairly powerful computers and a host of sensors plus the necessary signal conditioning circuitry. It is for this reason that the primary interest at this facility is with data buses as the need for high bit rate buses is real.

3.3 Company C

Company C is a large aerospace organization primarily interested in utilizing fiber optics for computer links and for telecommunications in a major new weapons system.

The engineers interviewed are assigned to the Electrical Electronics Materials Engineering group of the Materials and Processes section of their company. Their primary concern is the development of specifications and standards for fiber optics with particular emphasis on those products intended for use on a new weapons system. Their applications then are in the telecommunications area for the system contract with cable lengths running for 6 KM and with data rates less than 12M baud. In addition, the use of other links to support this program would be relatively short (100M) and would have even lower data rate requirements. They have one 4-1/2 KM data link in operation at present as part of an IR&D program. Their prime internal interest for fiber optics is for computer data links. As of yet, they have generated no internal specifications or standards, but they currently are in development. There are a few systems design people looking at fiber optics for the MX program. They seemed to be very interested in what other companies were doing.

3.4 Company D

Company D is a major aerospace company with a great deal of background in space vehicles, systems, and electronics. They are heavily involved in both fiber optics (F.O.) and integrated optics (IO).

The company now has many space related fiber optics programs in progress. They have no qualms about using present hardware in space. Hermeticity is not a major concern. The primary activity in this department is laser communications and integrated optics. All fiber optics used here is coupled to the integrated optics activity and is, therefore, single mode. This department has worked contracts which include an analysis of fiber optic components.

At present there are three integrated optics related contracts in progress in the department. These are: 1) A wavelength diversity MUX development program. The device developed combines planar optical waveguides, luneberg lenses, a chirp diffraction grating, and integrated detectors on a silicon wafer to provide a complete multichannel receiver on one chip. 2) A program to develop coupling techniques for optical fibers and injection lasers into planar waveguides and 3) a program on integrated optics correlators. Other activities at the group include the development of injection laser pumped YAG lasers for space-ground and space-space laser communications links. Data rates being used on some of the F.O. and IO systems are to 2 GHz. Gallium arsenide electronics are being used at these frequencies. To cover the above activities, there are 5 full-time engineers, 6 part-time engineers, and 5 part-time technical support persons and at least one dozen labs. Because of their work on laser communications, this group fabricates their own injection lasers (ILDs). They buy the semiconductor wafers but do all further processing which includes dicing, cleaving, surface depositions, bonding, and packaging. They claim up to 23% efficiency in their ILDs. They seem to have no reliability problems with the ILDs but did state that knowing how to handle them does avoid a lot of potential problems. They did blow many when they were first using them but alluded to optical problems such as reflections being the cause rather than electrical or thermal abuse. They did not seem to have any fears of using their product in their space applications without hermetic sealing.

3.5 Agency E

They are currently engaged in the evaluation of various fiber optic components for use in space and in space-related applications.

At this facility, a visit to the laser section was made. Activities here include the evaluation of plastic clad silica fibers at low temperatures and development of fiber testing technology. They are currently getting ready to evaluate several European fibers. They are using an auto test system from E.G.G. which is based upon a HP 9875 calculator and a HP digital plotter. This unit is similar to the one marketed by Gamma Scientific. As the program is just starting, no data is yet available.

3.6 Company F

Company F is a small manufacturer of fiber optic test and assembly equipment and is also a buyer of some fiber optic components used in their equipment line.

This company is a relatively new manufacturer of fiber optics test and assembly equipment. It is a relatively small company: 1 engineer, 1 sales, 1 office, 2 technicians, with two products on the market, a time domain reflectometer

(TDR), sold under their name (also marketed by another company under their own label), and an arc fusion splicer. The products seemed of good quality and technical merit. The company has no specification on the components they purchase other than minimum power output requirement (3W peak) on the injection laser purchased. They say that although power levels vary from lot to lot they do meet requirements and that so far they have had no field failures on the diodes and only one failure on the fiber optic coupler which they manufacture themselves. The detector used in the system is a photo multipler tube (PMT). The resolution of the TDR seems accurate enough for general use, a 2-meter length of cable being easily resolved. Total cable length measurement capability is limited to 60 db both directions. This is a guaranteed limit for 63-1/2μ core Corning cable. The device seemed to be able to display small bending losses in a cable and it can be used to determine cable attenuation by use of the Raleigh Back scattering portion of the display. Although the unit does work well, it seems somewhat overpriced.

The arc splicing instrument was demonstrated and seemed to work well. It has all the knobs and positioners one needs to align the fibers and control the arc power and time. The optics are AO stereo zoom and do a good job. Splice loss averages 0.25 db with a typical telecommunications fiber. This unit will handle fiber to 400μ and it has been used with 600μ fiber. The instrument again does the job but is expensive.

Laser diodes purchased and used in their equipment have had no field failures. Parameters do vary from lot to lot but are within data sheet limits.

3.7 Company G

This company is a large manufacturer of conventional connectors and is in the process of developing a line of fiber optic connectors and related products. The connector they have developed has been well received by most users.

The company expects a wide market for fiber optic products in both aerospace and aircraft applications as well as in ground links.

The company has developed a lensed single contact fiber optic connector for 125 micron O.D. graded index single fibers that requires no epoxy or the associated grinding polishing operations. The system uses a cleaved fiber and a plastic lens with a high refractive index fluid interface to provide the optical coupling. The system does work and is suitable for field use and repair as a special tool is provided which cleaves the fiber and crimps it and cable strength members to connector hardware to provide strain relief and optical positioning and alignment.

Early models of the system utilized quite large (1/2 inch diameter) lenses so that the total connector size was much larger than one would desire in most applications. A newer lens system which is 1/8 inch in diameter and which could fit in a standard #12 contact is now being developed and is being sampled. This new system provides a basis for much smaller single contact connectors and multicontact connectors now in development.

While the connection system described has many advantages, it should be pointed out that a liquid interface is prone to both contamination and leakage and so its usage could be limited. The connector has been subjected to standard connector shock, vibration, and temperature tests with no deleterious results.

New production facilities are being readied and the move to these facilities is scheduled in early 1980. This move will provide the needed production capacity to supply anticipated requirements.

3.8 Agency H

This agency has done extensive research in the application of fiber optics in underwater systems.

The engineer interviewed at this government agency is head of the fiber optic systems branch and is presently engaged in the development of both fiber optic and integrated optic systems for primarily submarine use.

The primary fiber optic appliction in work is the development of a phased array sonar system using upwards of 1000 sensors and individual fiber links to onboard data reduction units. Each link has an outboard wide bandwidth analog transmitter and an inboard receiver unit plus signal conditioning circuitry. As weight savings is a prime consideration in such a system, use of hybrid circuit transmitters and receivers is contemplated. Development of discrete part units has been completed, but the present contractor does not have hybrid circuit technology capability. As the system is being developed for surface ship use as well, the potential requirements are quite large. Production of the first units is scheduled for 1982.

Besides the sonar development, the agency is investigating fiber splicing utilizing V-grooves, initiating a study phase on a data bus for underwater use and studying optical data processing. In the optical data processing area, the agency displayed an integrated optic, single mode heterodyne receiver. The purpose of this receiver is to realize a wideband link capable of operating in the 2-4 GHz region.

This agency feels the need for standards on fiber optic components as well as improved component reliability. Installation and lack of suitable components for pressure bulkhead seals are of prime concern.

3.9 Agency I

This government agency has several contracts active in the area of space applications for fiber optic systems.

The engineer visited is a representative on the tri-services committee on standards, specifications, reliability, and testing for fiber optics. He is also project monitor for other space-related programs. The engineer's concerns are primarily at the system level but he is vitally interested in component technology because of its system impact. Primary emphasis was that fiber optic component standards should be based upon that of systems requirements rather than what industry dictates. He suggested that space systems be analyzed in detail so that optimum sizes and materials could be used in the development of fibers and cables for example. Prime considerations for such a cable might be low outgassing, low coupling loss, wide temperature range and radiation resistance while low loss, dispersion, and bandwidth length product might be of secondary concern. He pointed out that the component survey which was part of a contract he monitored did provide some guidelines for components in space applications.

3.10 Company J

Company J is a major manufacturer of fiber optic fibers and cables. They have done considerable research in radiation resistance in space applications.

The company did not offer much information concerning standard fibers. They are capable of drawing any fiber configuration (within a given design criteria) and, because their products are very specialized, offer no standard fiber for potential NASA applications.

Their company has just recently moved their fiber optic cable manufacturing facility. New drawing towers are being put into operation but, at present, no fiber is being drawn for production. The company is producing a wide range of primarily single fiber products and will still provide fiber bundle cables. Although their present market is aimed at the telecommunications area, they are in the process of developing large core products suitable for aircraft/aerospace applications. The development of radiation resistant fibers is of prime interest.

When this facility is fully operational, they should be capable of providing fiber optic products for most applications with relatively short lead times (4-6 weeks). However, at present in the transition stage, some difficulties in procurement can be expected.

3.11 Company K

Company K is a major telecommunications firm with over 2 years of actual field experience.

Company K developed, built, installed, and field tested the fiber optic links for one of the independent phone companies. Their equipment includes a T-3 rate (44.7 mbit/sec) digital telephone system (672 simultaneous phone conversations) and a 6-channel analcg link. The digital system is designed for heavy traffic trunk line use between telephone office centers, while the analog link is suitable for areas of high background noise such as power generation stations or railroad yards.

As compared to most companies interviewed who are using LEDs in their digital systems, Company K is involved with injection laser diodes (ILDs). Of the companies interviewed, Company K had unique applications, being telecommunications oriented as opposed to computer interconnects.

The fiber optic cables are installed by an outside company. As the links installed to date have been of a field trial/prototype nature, Company K has been installing and monitoring the links themselves. Reliability has been generally good with the exception of some early difficulties involving the ILD assemblies used in the T-3 system. These problems have been traced to contamination of the facets on the laser diodes. Epoxy outgassing is suspected as a contributor to the contamination. This problem is being solved by switching to a recently developed hermetic ILD package that is already pigtailed with an optical fiber.

The analog system uses an LED as the light source as compared to the ILD of the digital system. To date, the only difficulty encountered has been in the self-heating of the LED. As the efficiency of the LED is dependent on its operating temperature and the temperature is dependent on the level of current (assuming a constant environment), the output of the LED will vary from the input current. In other words, the diode linearity is effected by its self-heating. The effect occurs very rapidly (within less than 1 nsecond). The amplitude variation can be compensated for electrically, but the phase cannot be corrected. The degree of effect varies from diode to diode so each case must be adjusted for separately.

Test equipment is viewed as adequate, but not good. Optical time domain reflectometers (OTDRs) need to be further refined and more equipment suitable for field use needs to be developed.

3.12 Company L

Company L is a manufacturer of fiber optic hybrids and systems. They have much experience in this field, having been in the business for several years.

They use outside suppliers for their active devices (LEDs, PIN diodes, APDs). The reliability of the systems is claimed to be 10^5 hours. Systems are designed and tested to meet MIL-E-5400K. It was felt that, due to physical limitations of the LEDs, the maximum operating temperature of the systems to be 100°C unless cooling is supplied. Although primarily concerned with developing the commercial market, they are able to match most military requirements except for the temperature limitations.

A large market for data bus systems is seen but the lack of an acceptable star-coupler is the main stumbling block to implementation. At the curent time, no field maintenance procedures exist and work is being initiated to correct this.

The lack of field test equipment is seen as a real problem. The equipment that is available is not very satisfactory. To measure loss in a system, both ends of the cable are needed. A known illumination is used at one end and the loss is calculated by measuring the drop in the output at the other end. This is not a very reliable method as minor changes in launch conditions can effect wide differences in the initial amount of light transmitted into the fiber. Optical Time Domain Reflectometers (OTDR) claim to be able to measure loss by monitoring the backscattering of light. However, they are not very reliable at this time and give unsatisfactory readings. OTDRs in general need more work in order to improve their reliability, accuracy, and flexibility.

Most connectors are also unsuitable for field termination. They require that the fiber/cable be epoxied to them. After the epoxy is dried, the ends of the connectors are polished (usually by hand). This is felt to be unacceptable in the long run and that a field installable connector should be developed.

3.13 Company M

Company M manufactures a line of photometers particulary well suited for use with fiber optics.

The accuracy of the photometers is 1% of their reading and is traceable to NBS standards. Field maintenance procedures to troubleshoot are provided. The photometers operating range is from 1 pw to 2W optical power. The devices can be damaged if exposed to higher energy levels, however, as most fiber optic links operate in the nW region and lower, the danger is not too great. Since temperature effects the efficiency of the photocells, the units are compensated to maintain their accuracy within the entire operating range.

The photometers use an LCD readout. This limits their operating range to 0°-50°C. The readings do not vary with time, i.e., there is no degradation of accuracy with time. The device is also limited to measuring light within a numerical aperture (NA) of .4. This is a limitation caused by the physical dimensions of the device. It will not be completely accurate in measuring the output of a fiber with a higher NA.

The flexibility and ease of use of the photometer is being enhanced with the introduction of several fittings allowing direct coupling of a connector to the sensitive area. Thus, cables that are already installed and terminated with a connector may be easily and accurately measured. This makes for easy determination of the magnitude of transmitted light, and allows for checking of proper installation of the cable -- microbending losses, pinching, damage, etc., all of which will reduce light output. The bit error rate (BER) of systems is normally optical power magnitude limitied, i.e., if the power drops too low, the number of errors increases. A means of accurately checking installed cables for loss (especially for noticeable changes in the loss of the cable from before installation) is a good way of checking for proper installation of the cables. This will ensure a higher reliability of the systems and guard against the use of a link which is only marginal to start with (due to installation induced losses) from dropping below acceptable levels of performance during the life of the system (temperature effects for example). Unfortunately, it is not a one-point measurement system -- both ends of the cable must be used in order to obtain a reading.

Improvements need to be made in available spectral analysis equipment as well as in OTDRs. They need to be made cheaper, more rugged, and be further refined. Company M is working on a method of measuring single fiber NA. Industry wide, little has been done to uncomplicate the technology.

3.14 Company N

Asynchronous and synchronous modem replacements, high speed data links, transmitter, and receiver modules are the fiber optic products of this company. The systems are of high quality and several hundred are in current use.

Company N is producing point-to-point data links in a wide variety of styles. Field maintenance procedure would be to replace the entire unit. However, to date, of the more than 400 units in service, only 3 failures have been reported. Two were from customers determining how flexible the cable was (they bent the cable till they broke it at the connector/cable interface), and the other failure was due to the accidental pouring of a cup of coffee into the modem while it was in operation (the cover had been removed to allow examination by the customer).

Due to the lack of data, no field failure modes have been determined. Many of the LEDs, however, have been rejected by their incoming inspection (they are bought from outside sources). Apparently there is a QC problem with some of their suppliers of fiber optic diodes. (At the time of the interview, they were purchasing diodes from 5 sources but were thinking of dropping two of them due to high rejection rates at Receiving Inspection.) The rejected LEDs either had optical power below their spec or had no power at all. Problems were caused by poor assembly of the diodes (chips improperly mounted or damaged). Supplier testing should have caught and rejected the defective diodes. The LEDs, which do pass the incoming inspection (essentially checking the optical output), are guaranteed for 10^5 hours.

The test equipment used was built in house and is available to customers. It can be used in the field as long as AC power is available. Since the links are designed for computer use (primarily), this is normally available.

A large potential for multipoint data bus systems is seen. The lack of suitable couplers is blocking the implementation of these systems. Connectors were also felt to be inadequate. They are expensive, hard to install, and not very effective. Company N modifies the connectors they buy to improve the coupling loss. They have not been limited or hampered by environmental differences or by the lack of standards (yet). A user's manual is furnished.

3.15 Company O

Company O is a leading manufacturer of electrical connectors. Recently, they have started producing fiber optic connectors including a bayonet-type, quick disconnect connector.

A large problem facing connector manufacturers is the newness of the technology. There are no standards on the cable structures, new structures keep appearing. It is hard to train workers to the necessary precision needed for low-loss connectors. Adequate test equipment is not available.

All of Company O's connectors are made to meet or exceed mil/spec, although they do not qualify to mil/spec. The connectors are not designed for underwater use. Heat is no problem, being only limited by a silicon gasket used. (Heat may affect the adhesives used to mount the fiber and/or the cable to the connector.)

Plans call for development of a field implementable connector. At present, the connector is suitable for lab (house) termination only. There are no immediate plans for a multiterminal connector.

Wear is not really a problem with the connectors. Repeated couplings do not increase the connector loss to any appreciable degree. Dirt, on the other hand, quickly deteriorates the coupling efficiency.

3.16 Company P

Company P is a major manufacturer of semiconductor devices. They have recently introduced fiber optic diodes mounted within connector assemblies.

Company P is interested in producing hermetic packages; but, there is no market for such and they cannot justify the expense to develop such products. No problems in meeting space/military requirements were expected; however, they believed that government funding is necessary to develop to the full requirements. The devices they currently sell will meet space/military requirements except for hermeticity and the LED operating junction temperature range of -30°C to +125°C.

Their devices are currently capable of operating in the 20-25 mbits/sec range. A Burrus LED, currently in development, will have a faster rise time and be able to operate up to 50 to 100 mbits/sec. The detectors they produce are capable of operation as fast as 50 to 100 mbits/sec.

ICs to support the fiber optic diodes are in development. Material dissimilarities are preventing the fabrication of active element and the support IC on the same substrate. The plans for the receiver support ICs include the use of two separate circuits. One IC would be mounted in the same assembly as the detector while the other IC would be in a separate package. The external chip would be standard while the chip in the assembly would be variable. This arrangement will allow plenty of flexibility in detector selection while minimizing part proliferation.

They have not been able to establish failure modes and mechanisms of their new device/connector assemblies as they are too new. Insufficient data was the reason given for the lack of conclusions. Of the units sold, so far, they have not received any complaints. Application notes are not available but are being prepared. They will include circuits for use with the devices.

The lack of testing standards makes it impossible to compare devices from different vendors. Each vendor uses a method which presents their product in the most favorable way.

3.17 Company Q

Company Q is dedicating itself to develop and produce optical fiber suitable for space and military applications.

Company Q feels that they have developed Plastic Clad Silica (PCS) fiber to the point where it is able to meet space and military requirements. They claim their product is able to meet environmental requirements (humidity, temperature, radiation) as well as display low attenuation (5 dB per kilometer). Radiation tests have been recently started using a Cobalt 60 source delivering 8000 rads per second. Fibers exposed to this radiation have exhibited a maximum increase in attenuation of 10 dB/Km.

Their fibers are also able to operate at -60°C. Most PCS fiber is capable of operation down to -20°C. The problem at low temperatures is due to material limitations of the plastic cladding. At lower temperatures the refractive index of the plastic begins to change, approaching that of the silica core. The numerical aperture (NA) of the fiber is a function of the difference of the refractive index between the core and the cladding. The NA of the fiber is a measure of the acceptance angle, the larger the NA, the wider the angle of light is able to propagate down the fiber. (Light which strikes the core/cladding interface at an angle greater than the NA is not reflected, instead, it travels through the cladding and is lost.) As the refractive index of the core approaches the cladding, the NA of the fiber begins to drop. As the NA drops, less light is propagated down the fiber.

The change in NA will be quite abrupt at the temperature limit of the fiber. A plot of NA versus temperature will show a "knee" at the lower temperature limit, with the NA rapidly degrading at lower temperatures.

Radiation effects are not so well understood. Investigations are underway to discover if radiation effects are at the core/cladding interface, only in the cladding, in the core, or perhaps combinations of the three.

They claim to have good field reliability. Their fibers are being used in several tests in severe environmental conditions. There have been no problems encountered to date (no data existed to back this claim). However, no field maintenance procedures are available, but are in the planning stage.

They feel that connector people have not been in enough communication with the cable manufacturers. This is particularly true in regards to PCS fiber. Termination of PCS fiber is difficult due to the plastic used in the cladding. Adhesives which adhere to both the plastic and metal are not satisfactory. Also, the core, because it is harder than the cladding, is not perfectly polished during end preparation. The core is compressed against the cladding and tends to protrude after the polishing sequence. The protruding core is very susceptible to damage, especially during the mating of two connectors. Company Q has solved this difficulty by developing a hard cladding sheath which replaces the original cladding at the termination point. They have also modified commercially available connectors to be suitable with PCS fibers.

3.18 Company R

Company R develops and manufactures fiber optic components and modules. They have been in fiber optic development for the military.

Various active fiber optic diodes, ICs to support them, and modules which combine both are produced by Company R. Their LED is optimized for fiber core size of 100 m or larger (short haul fiber). It comes in a hermetic package and uses a glass bead lens to focus the light into the fiber.

The transmitter and receiver modules were developed as part of a military contract. The military version modules contain hermetically sealed and screened LEDs (transmitters) and extended military ICs.

They have not been able to isolate any specific failure modes or mechanisms yet (aside from bulk degradation of the LEDs). Several hundred units have been deployed in the field. There have been no LED failures and only a few mechanical failures.

Production line testing is performed on both the devices and on the modules. Environmental tests are performed per MIL-STD-883. Lifetime tests on the LEDs are conducted in 30 unit lots. The LEDs are run at 100 mA at a case temperature of 25°C. The average for 5000 hours of running is a 2% loss in output power (worse case loss is 7%). Lifetime projections of the LEDs (the point where output has degraded by 3 dB) are in excess of 10^5 hours. No accelerated temperature tests are performed. There is controversy as to the accuracy of accelerated temperature tests performed on fiber optic sources. The failure modes and mechanisms at accelerated temperature are not necessarily identical to those at room temperature which makes projections from such data unreliable.

The only testing problems they have encountered have been in testing the receiver modules. The problems were due to the sensitivity of the modules. They have no field test equipment. Derating information is being developed.

3.19 Company S

Company S is one of the largest producers of semiconductor devices. They have a line of low cost fiber optic devices.

This company plans to pigtail optical fibers to their diodes. The process they use will be fully automated by the early 1980 time frame. They are currently using a plastic fiber which limits their temperature range to 0°C to 70°C. The packages are not hermetically sealed. Plans are in effect to produce a hermetic package during 1980.

At the present time, they do not possess extensive reliability data. To correct this deficiency, they are in the process of starting up a large reliability testing program on their devices. By the third quarter of 1980, more data will be available. They do not burn in their commercial grade LEDs.

They are aware of the deficiency in user information on fiber optics. Most suppliers do not have information available to train people to the use of the full potential of fiber optics. (Unlike, for example, microprocessors, for which several companies have seminars on their use.) A training program in fiber optics will be started in 1980 by this company. The first sessions will be in Chicago. Application notes are also being developed and should be available in 1980.

Company S is concentrating on the commercial market for fiber optics. They see applications in computer links, industrial control, instrumentation, and similar data lines. In their opinion, widespread use in space applications will be after fiber optics is proven in the commercial field.

The test equipment they use is designed in house. They have encountered no testing problems.

3.20 Company T

Company T is a major manufacturer of LEDs and ILDs. They have extensive experience with sources and have been involved with military projects.

The device with which Company T has the most experience and expertise is the pulsed laser diode. Pulsed laser diodes are not suitable for communication purposes. They do, however, emit much higher levels of light. As the diodes are made of similar materials as communication laser diodes (which they also produce), the extensive experience forms a strong background for their work in fiber optics. They have been involved in a 6-year program to develop a mil/spec pulsed laser diode.

The pulsed laser diode they make meets military specifications with a temperature range of -55 to +70°C. The pulsed laser diode will be used as part of an optical proximity fuse for an air-to-air missile. They are also working on a system to install a pulsed laser diode into a space satellite. The system will be delivered in March of 1980. Several thousand pulsed lasers are produced a month.

They have produced special order LEDs for military programs. The LEDs are capable of operation up to 50-60 mHz in a temperature range of -55° to +70°C. They have not received requests for LEDs that operate up to +125°C. They felt that the consensus of opinion was that +70°C was about the top temperature limit for LEDs. They have had no problems with hermeticity or shock. Pigtailed packages which are hermetic to MIL-STD-202E are available. The temperature limitations of ILDs will be overcome by the use of thermoelectric coolers (TEC) and optical feedback.

They have identified four predominant failure mechanisms. Two of the mechanisms are common to both LEDs and ILDs and will be discussed first.

Infant mortality is when the diode degrades at a rapid rate becoming unacceptable in less than 200 hours. A hundred-hour burn in of the diodes reveals those which are affected by infant mortality.

Bulk degradation is the gradual decrease in optical power under constant drive current. In well constructed diodes, this decrease will take over 10^5 hours to degrade the diode performance below acceptable levels.

The other two failure modes are unique to laser diodes. ILDs have facets or mirrors along two edges of the diode. This forms the cavity which produces the lasing of the diode. Damage to these facets is the cause of the other two failure mechanisms.

Catastrophic facet failure is abuse originated. When the ILD is run at output power greater than the specified maximum, the facet is literally blown off the face of the diode.

Facet erosion, like bulk degradation, is a very gradual process. The surface of the mirror slowly degrades. The time frame for erosion to cause failure of the diode is similar to that of bulk degradation (10^5 hours). It is not clear whether bulk degradation or facet erosion is the dominant factor of ILD lifetimes.

Application notes are provided with the diodes. The supplier admits that the industry, as a whole, has not provided enough information for the user.

3.21 Company U

Company U builds exclusively injection laser diodes (ILDs), including some mounted with control circuitry. They are attempting to develop the ILD to the point where mass production is possible. Mass production will lower the price to the 50 to 100 dollar range.

The high cost of ILDs is delaying their widespread implementation. The cost of current ILDs range from a few hundred to a few thousand dollars apiece. Obtaining higher yields and being able to reproduce the results will lower prices. Mass production is the key to the problem. Company U is dedicating itself to developing ILDs to the point where mass production is possible. Many ILD structures are too complex for this. They are hand made by engineers in laboratories. This is acceptable only if small numbers need to be produced. Company U feels that mass production will lower the price down to the 50 to 100 dollar range.

ILDs are now available in hermetic pigtailed packages. Attempts are being made to have the package standardized throughout the industry. This will make possible interchangeability between different suppliers, second sourcing, and considerably ease design considerations.

The performance of ILDs is greatly improved over that of two years ago. The bandwidth is large enough for any practical applications (over a gigahertz). The power output of ILDs is adequate for almost all long distance links. Although no testing has been performed, it appears that radiation does not greatly affect them. ILDs were recently used in some nuclear test blast monitoring equipment.

All the other semiconductor devices were knocked out except for the ILDs. It was theorized that the radiation did not affect the ILDs because their active areas are buried within the diode, unlike other semiconductor devices where the active area is exposed. ILDs also have low thermal impedance. The threshold (drive current necessary for lasing to start) increases by only 30% as the diode temperature increases from 25°C to 70°C. Lifetimes of the diodes are comparable to other ICs (10^5 - 10^6 hours).

Multimode lasers are superior to single mode lasers (longitudinal modes). A single mode laser will create interference patterns in the fiber which will hamper the detection, creating an unacceptable number of errors. The line width is the controlling factor. A multimode laser has an effective line width equal to the separation of the modes while a single mode laser has a line width of only the mode width. The wider the line width, the less will the interference pattern predominate. Dispersion is not a problem with multimode layers as the range in frequency is still quite small.

Four main failure mechanisms were identified. Two were related to the facet and two to the crystal. The first mechanism is catastrophic facet damage caused by customer abuse. The customer exceeds the maximum power rating and the facets are quickly destroyed. It was pointed out that the power density at the facet is 1 Mw/cm^2 which is the highest for any laser source (gas, solid state, etc.).

The second mirror related failure is facet erosion. Facet erosion is the slow process whereby the facet is gradually destroyed. A theory to explain the cause of facet erosion was presented.

At the moment of cleaving, the facet becomes very active, combing with molecules of oxygen and carbon in the air. Spectographs of the diodes show oxygen and carbon molecules n the first 50°Å behind the edge of the facet. A photochemical reaction slowly erodes the facet. At power levels above 5 mw, the process is speeded up, while below 5 mw the rate is constant.

The two crystal failures are dark line defect (infant mortality) and bulk degradation. Dark line defect is the movement and combination of dislocation centers. Diodes with this failure mechanism can be screened by an initial burn in. Bulk degradation is the diffusion of impurities into the active region. This reduces the recombination efficiency, cutting down on optical power. This failure mechanism is common to all ICs.

European companies are expending substantial effort to understand ILDs. American companies which are interested in ILDs have not put forth the effort to learn about them. This causes them problems when they try to use the diodes in their systems.

3.22 Company V

Company V is a large manufacturer of connectors. They have a long line of fiber optic connectors including several multitermination connectors.

Company V felt that lack of standards is affecting connector design and development. With the wide variety of cable configurations, connector manufacturers spend a large part of their development effort in trying to accommodate as many configurations as possible. Standards will lower costs of connectors. Fiber sizes and cable configurations need to be standardized. Standardization will also allow different connectors to be directly evaluated against each other as specifications will also be set.

Dirt buildup is the major problem with connectors. The connector coupling loss will start to slowly degrade. Cleaning the end of the connector will restore the original loss value. Another problem is breakage of the fibers. This can occur during termination or handling.

The problems of adhesives were addresesed. Available adhesives do not bond to the fiber and the connector very well. This is especially true under temperature cycling. Some fibers use a silicon cladding to which it is impossible to bond. Either connector design will move away from the use of adhesives or adhesive technology will solve the problems. (The current situation is not an acceptable long term solution.)

The difficulty of the mechanical retention of the core of PCS fiber was discussed. The plastic cladding is much softer than the glass core. The core can move independently of the cladding, so that bonding to the cladding will not guarantee the position of the core. As coupling losses are dependent on alignment precision, the shifting of the core position can cause major connector losses. Also, since the core can protrude beyond the end of the connector, it is susceptible to damage. Another problem is the temperature range of cables. Under temperature cycling, the expansion and contraction of the cable may break the fiber, normally at the connector/cable interface.

3.23 Company W

Company W manufactures and installs fiber optic cable and systems. They have over 2000 links in operation, split about 50/50 between commercial and military customers.

Installation of the links is normally performed by the customer, but under Company W supervision. The customers personnel are taught how to do the installation. Termination procedures are available; however, there are no field maintenance procedures. The problems of PCS fiber termination have been solved. A large manufacturer of computer equipment uses Company W PCS fiber in commercial systems.

Equipment is being constructed to allow mechanical testing of the cables to military standards. Tests such as bend, crush, and stress will be performed. The use of existing cable standards (military) will allow an evaluation of their fiber optic cable as opposed to conventional electrical cable. They are not equipped to handle military standard chemical and radiation tests. Research is continuing on materials and procedures.

Of the over 2000 links installed in the last two years, there have been only about 15 failures. No details as to failure causes were supplied. Most of the customers have special applications which require fiber optics. These include data links in high noise areas, places with electrical grounding problems, and need for a low bit error rate.

3.24 Company X

Company X manufactures fiber optic cable and complete systems. They have experience in several areas of fiber optics, especially in cable.

Company W felt that standards are premature. Standardization at this time will inhibit development of the technology. Cable configurations are currently not optional. The knowledge of the materials is available, but the implementation of materials into cables is not fuly developed. Current cables can meet various aspects of military standards, but a single cable cannot meet all the standards.

The use of a loose-tube construction (common to early cables) where the fiber lies loosely in a large inner jacket has problems which are almost unsolvable. At low temperatures, the tube contracts, pinching the fiber (especially glass on glass), and inducing microbending losses, which increases the attenuation. Current cables have a temperature range of -20°C to +65°C. Performance beyond this temperature range has not been fully investigated. Cables which can operate beyond this range have been made, but not consistently or reliably. More work is also needed in development of PCS fiber and cable. Methods to strain relieve the fiber at the connector are not optimal. Also, the low temperature problems of PCS need to be solved.

Connectors are a problem. They are the least developed of the components. Adequate multiterminal connectors are not available. Connectors are not able to perform over the temperature and environmental range of military standards. Strain relief of multiterminal connectors is not adequate.

Fiber optic equipment is now as reliable as electronic equipment. They have had no field reliability problems.

Available test equipment is adequate. Dispersion and bandwidth measurements are not possible in the field. The OTDR needs to be further refined.

3.25 Company Y

Company Y is a manufacturer of connectors. They produce both single terminal and multiterminal conectors.

Company Y has made thousands of fiber optic connectors. The connectors have a temperature range comparable to cable (-20°C to 60°C) and are nonhermetic. A connector has recently been developed which is fully hermetic. They are attempting to integrate their efforts with cable manufacturers.

They are interested and involved in the military market. The military market could open up in one or two years. Currently, they are working on a contract to develop high density multiple fiber connectors. This will support efforts to develop conventional multiterminal connectors.

Field terminations are difficult without access to power. Providing an adequate environment for epoxy curing as well as end polishing is the problem. Epoxies are seen as the weak link of connectors. Epoxy lifetimes are being investigated now. If possible, connectors without epoxy would be developed but they are not sure how to approach the problem.

3.26 Company Z

Company Z is a manufacturer of ILDs and high data rate systems.

Company Z plans to enter the military market as rapidly as possible. Although currently not competing for military contracts, they are keeping track of the ongoing contracts of other manufacturers. In the meantime, they are optimizing their product line. Their first goal in this process is developmnt of an ILD and package capable of operation from 0° to 70°C. This will be completed in the first quarter of 1980. One of the main problems is finding a suitable thermoelectric cooler (TEC). No available cooler will operate from -55° to +125°C. The cooler they plan to use has ben in evaluation since July of 1979. It will operate in the 0° to 70° range.

Their volume of production is low at present and yields of devices are typically less than 25%. These are two of the reasons for the high cost of current ILDs.

Development work is still in progress. The diodes are so new that people do not fully understand all the ongoing mechanisms in the laser. Understanding of the ILD will result in higher yields and more dependable devices. For example, at the ends of the active region next to the facets, heat instead of light is created. The depth of this heat producing area increases with time. This is a degradation phenomena being studied now. A fuller understanding as to the principles of the phenomena will result in longer lived lasers.

Company Z is spending a lot of time and effort to identify optimum materials and processes that go into the manufacturing of ILDs. They hope to increase the yield and reliability while dropping the price.

4.0 ANALYSIS OF THE DATA

After the companies were visited, all data gathered from the survey forms, interviews, and literature search were collected and analyzed with respect to standardization, reliability, and applications. Because of the relatively little usage of fiber optics technology by the military, no hard data exists to back up the claims in the area of reliability. In most cases, the users with operational systems (commercial firms) are not keeping accurate accounts of field failures and are not performing failure analysis on devices that are returned from the field. This makes the analysis of the data very subjective.

The analysis of this data/information, therefore, represents the accumulation of the experiences and opinions of the experts on fiber optics. The findings are, however, believed to be an accurate assessment of the fiber optic technology. Strengths and weaknesses of the technology have been identified as well as current standardization effort. The results of this analysis can only be fully verified by actual hard data on field experience and failure rates.

Each of the fiber optic component/categories will be addressed separately below.

4.1 Sources

The summary of the analysis on fiber optic sources is contained in Tables 4.1 and 4.2. There are two basic types of LEDs - edge emitters and surface (Burrus) emitters. Figure 4.1 explains the differences between the two types. Of the two, the Burrus diode is more widely used due to its generally better performance. It is also a more expensive device (as much as a factor of 100 more expensive, depending on the quality). As the top of the Burrus diode is etched away to expose the active area, the devices normally comes pigtailed. Until recently, these devices were not hermetically sealed. One company now claims to have developed a hermetic pigtailed Burrus diode.

COMPONENT: INJECTION LASER DIODES (ILD, DOUBLE HETEROSTRUCTURE GaAlAs)

SUITABLE FOR CURRENT SPACE USE:	YES (WITH PROPER DESIGN CONSTRAINTS)
RELIABILITY:	1%/1000 HOURS
STANDARDS (MILITARY/INDUSTRY):	1982 LARGE VARIETY OF DEVICES, NEW TECHNOLOGY
SPACE QUALIFICATION:	1983 DEVICE TO BE EVALUATED COMPARED TO STANDARDS
APPLICATIONS:	HIGH DATA RATE TRANSMISSION, HIGH EMI, EMP AREAS
FAILURE MODES AND MECHANISMS:	INFANT MORTALITY (FIRST 100-200 HOURS - CRYSTAL DEFECT RELATED). FACET DAMAGE (ELECTRICAL OVERSTRESS, CURRENT SPIKES - HIGH OPTICAL POWER DESTROYS FACETS). BULK (GRADUAL). DEGRADATION (MIGRATION OF DOPANTS INTO ACTIVE AREA, GRADUAL FACET EROSION - LIMIT OF DEVICE LIFE).
LIMITATIONS:	DEVICE IS TEMPERATURE SENSITIVE. SHOULD BE MAINTAINED AT 25°C OR LESS FOR MAXIMUM LIFETIME AND OUTPUT POWER. SENSITIVE TO ELECTRICAL OVERSTRESS, MUST BE PROTECTED FROM ANY CURRENT SURGES (EVEN OF LESS THAN 1NS).

TABLE 4.1 INJECTION LASER DIODES ANALYSIS

COMPONENT:	LIGHT EMITTING DIODES (LED, SURFACE EMITTER (BURRUS), EDGE EMITTER GaAlAs)
SUITABLE FOR CURRENT SPACE USE:	YES (WITH PROPER DESIGN CONSTRAINTS)
RELIABILITY:	1%/1000 HRS
STANDARDS (MILITARY/INDUSTRY):	1981 CURRENTLY BEING GENERATED
SPACE QUALIFICATION:	1982 (IF REQUIREMENTS ARE DEFINED)
APPLICATIONS:	LOW TO MODERATE ($\leq$50MHz) DATA RATE TRANSMISSION. LIMITED TO MODERATE LENGTHS ($\approx$2Km OR LESS) TRANSMISSION. HIGH EMI, EMP AREAS. ANALOG APPLICATIONS.
FAILURE MODES AND MECHANISMS:	INFANT MORTALITY (FIRST 100-200 HOURS - CRYSTAL DEFECT RELATED). BULK DEGRADATION (GRADUAL MIGRATION OF DOPANTS INTO ACTIVE AREA - COMMON TO ALL IC'S).
LIMITATIONS:	CURRENT DEVICES LIMITED TO <100MHz OPERATION. WIDE SPECTRAL WIDTH CAUSES DISPERSION PROBLEMS IN LONG LINKS.

TABLE 4.2 LIGHT EMITTING DIODE ANALYSIS

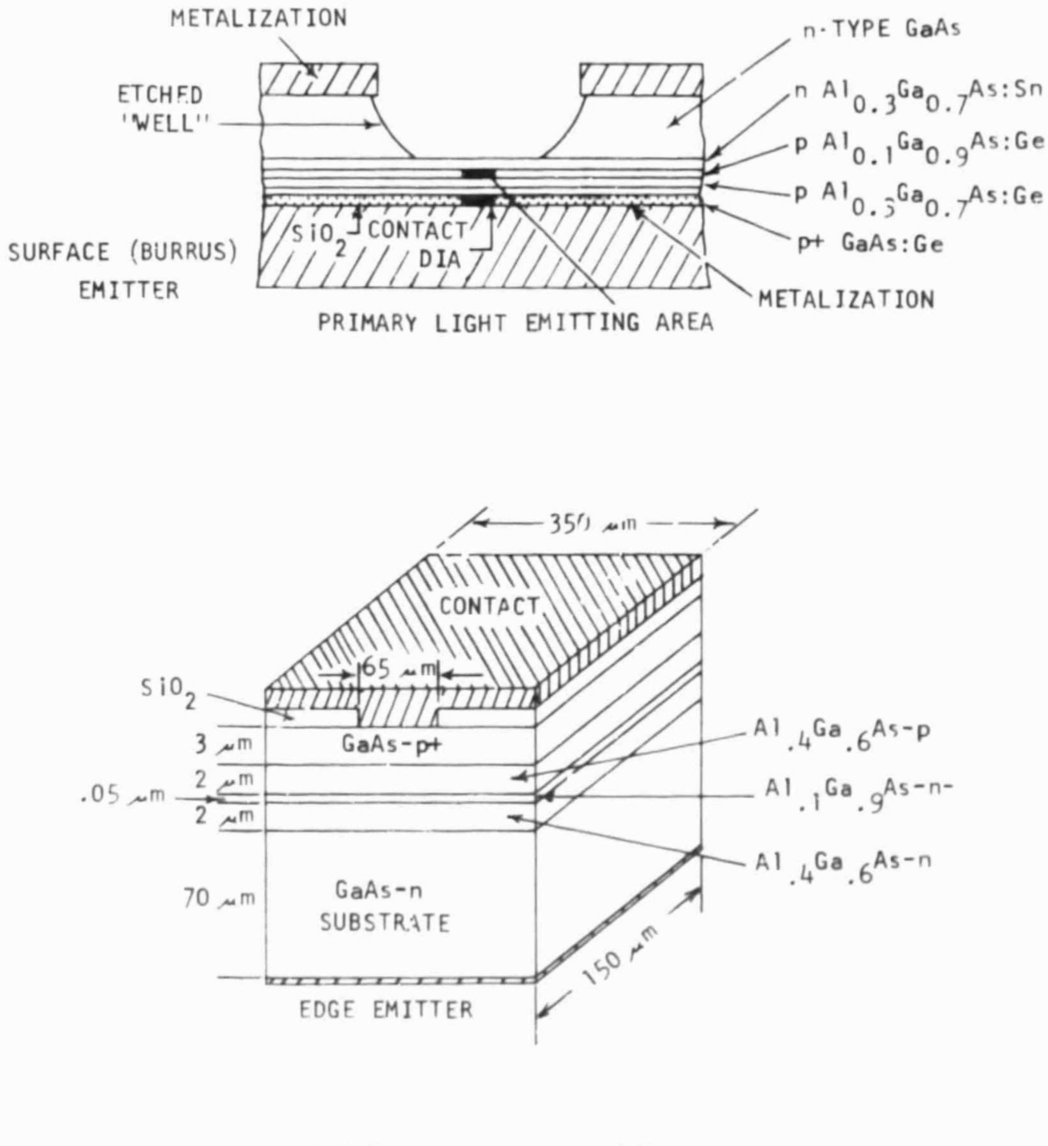


FIGURE 4.1 LED STRUCTURES

Edge emitting diodes are normally mounted in a package incorporating a reflector. As the light is generated in a plane parallel to the junction and propagates in all directions, coupling efficiency (espeially into single fibers) is lower than for Burrus diodes, as shown in Figure 4.2.

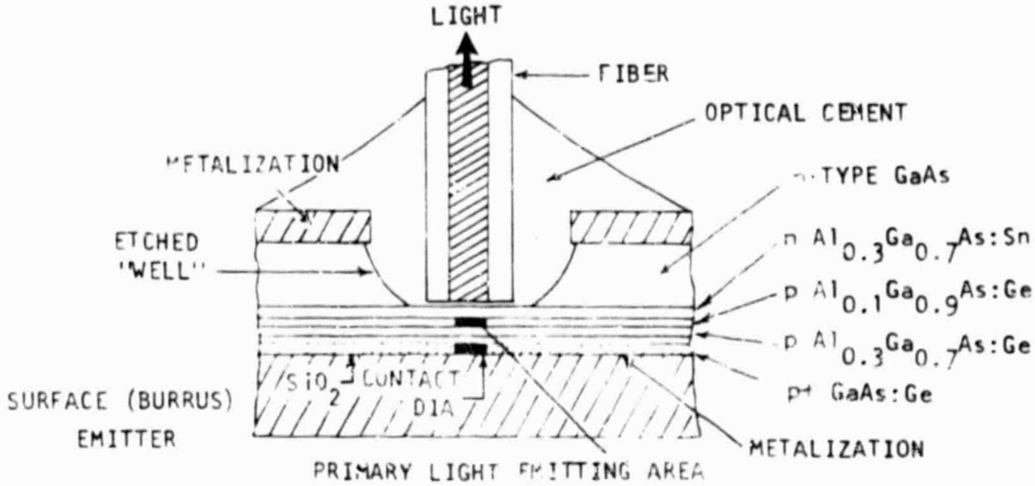
Surface emitting diodes with lenses to focus the light into the fiber are another solution to achieve a hermetic seal, as shown in Figure 4.3.

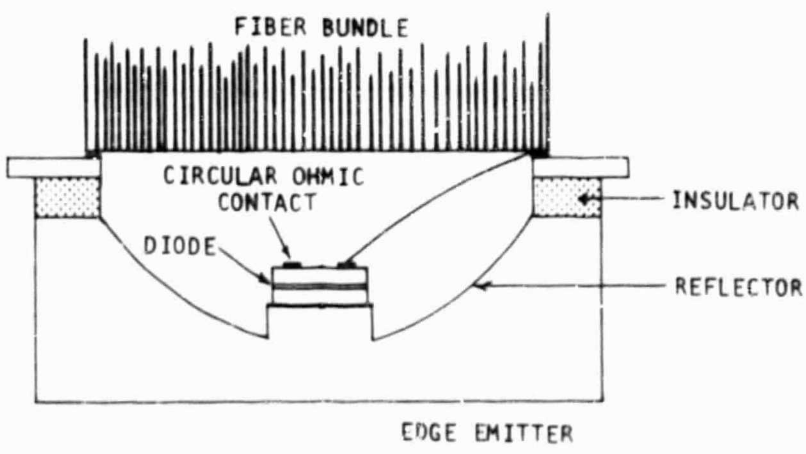
Companies producing LEDs for military projects report that the temperature range requested has been -55 to + 70°C instead of the normal +125°C requirement. Companies report being able to meet environmental, shock, and other mil requirements without too much problem.

Reliability of the devices is good although little hard data is available. There have been few field failures and lifetimes of over 10^5 hours are estimated. One company claims their new LED will have a failure rate of 1.5×10^6 hours. The two dominant failure mechanisms, infant mortality and bulk degradation, will be covered in the injection laser diode (ILD) failure mechanisms description.

LEDs come in a wide variety of packages. This increases the difficulty of use as there is little interchangeability between different manufacturers. Available packages have not been optimized for coupling efficiency, therefore, more practical designs need to be developed. Unfortunately, with the technology being so new, little thought has been given to developing packaging, most of the effort has been devoted to refining the chip.

Injection laser diodes (ILDs) proved to be a pleasant surprise, being much further developed than anticipated. ILDs have the reputation of being fragile and short-lived. Most of this goes back to the time when they were first introduced. Not enough applications information was provided. This led to many early failures, especially with people who were operating them for the first time. A standard remark heard at that time was that when you first start using them you're going to burn out a few. Not enough information on how to avoid early burnout was provided. ILDs are extremely sensitive to current spikes and transients. Unless special precautions are taken, merely turning on the power





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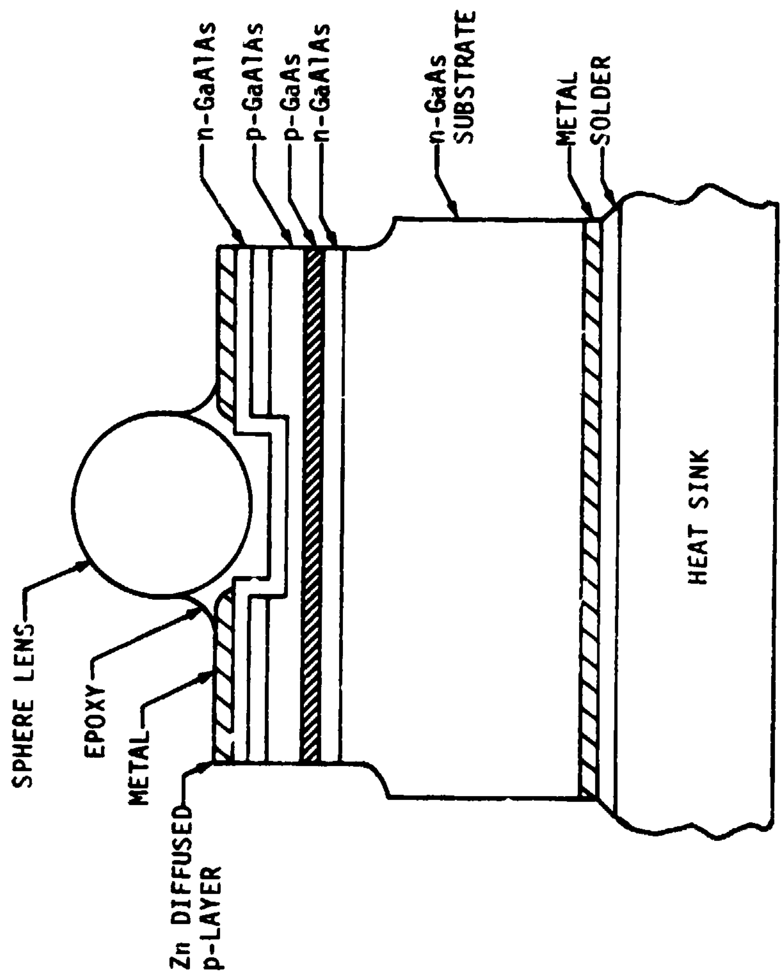
OF POOR QUALITY

FIGURE 4.2 PIGTAILING OF LED STRUCTURES



CROSS SECTION OF LED WITH LENS

FIGURE 4.3

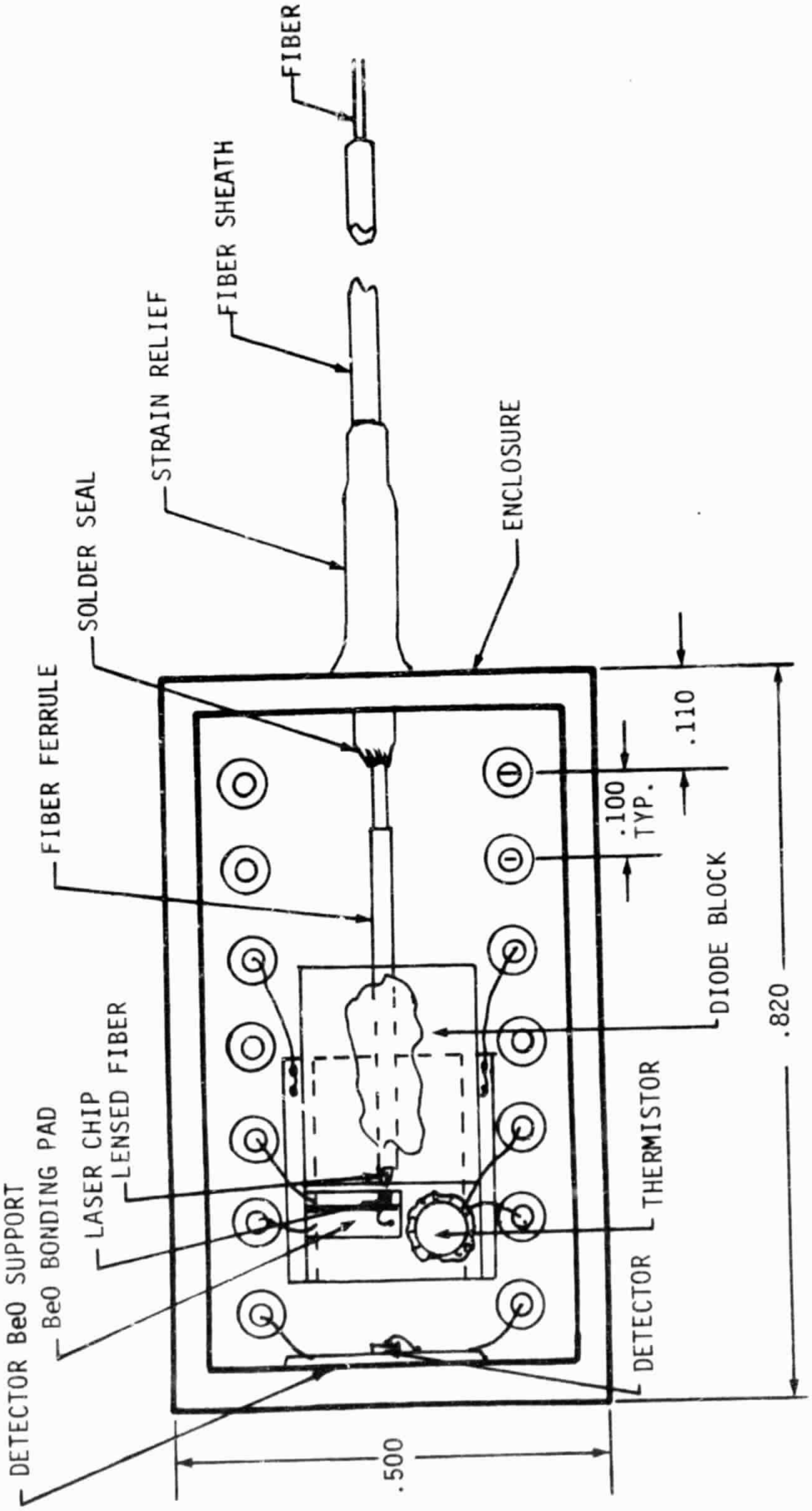
supply running the ILD is enough to burn it out. At roughly a thousand dollars apiece, people quickly formed a bad opinion of ILDs after killing a few. This prejudice against ILDs still persists and, hence, their bad reputation.

The interviews during the survey tended to dispel these rumors. Lifetimes are now comparable to other ICs ($10^5 \rightarrow 10^6$ hours). Unlike the packaging of other fiber optic devices, ILDs are being standardized (into a 14-pin DIP package), as shown in Figure 4.4. The package will have a standard pin layout. This will allow interchangeability between the various suppliers. The packages are large enough to include theremoelectric coolers, a PIN reference diode, a thermistor, and, perhaps eventually, the driver electronics. The package also incorporates a hermetic fiber pigtail seal. The fiber is coated with metal (apparently with equipment used for metal deposition in the fabrication of the ILD chips and other IC devices) and soldered to the package. Although new and still a prototype device, it is a welcome change from the packaging concept used with the other fiber optic diodes.

Another block in the way of more widespread use of ILDs is their extreme high price. Bare diodes mounted on a heat sink cost anywhere from a few hundred to over a thousand dollars. Pigtailed diodes, or diodes in special packages, are even more expensive. The reasons given for the high price are the high developmental costs that need to be recovered, the complex structure, the high demand, and the low yields of the devices.

One of the reasons for the low yields is that the structures are extremely complex. See Figure 4.5. Currently, the diodes are being produced by hand in laboratory-type environments. One company is working at refining the ILD to the point where they can be mass produced like other semiconductor devices. This will lower the price to the 50 to 100 dollar range. Many of the structures used are not suitable for mass production and it is hard to see how the manufacturers will be able to significantly lower their cost.

For a while, effort was expended on producing lasers with a single longitudinal mode instead of several modes. Figure 4.6 represents the differences between a multimode and a single mode spectrum. Recently, evidence supports the use of



14 PIN ILD DIP

FIGURE 4.4

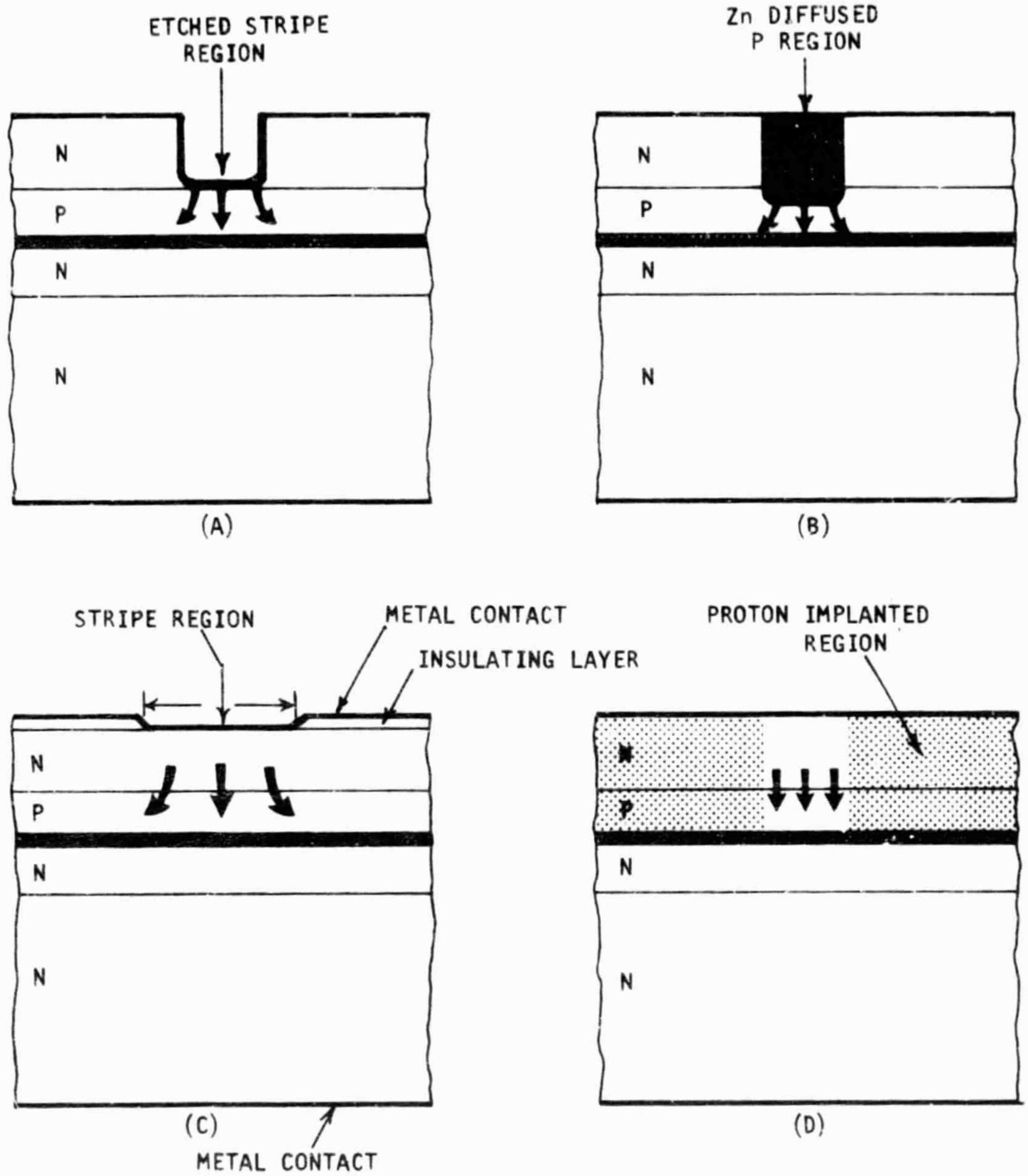
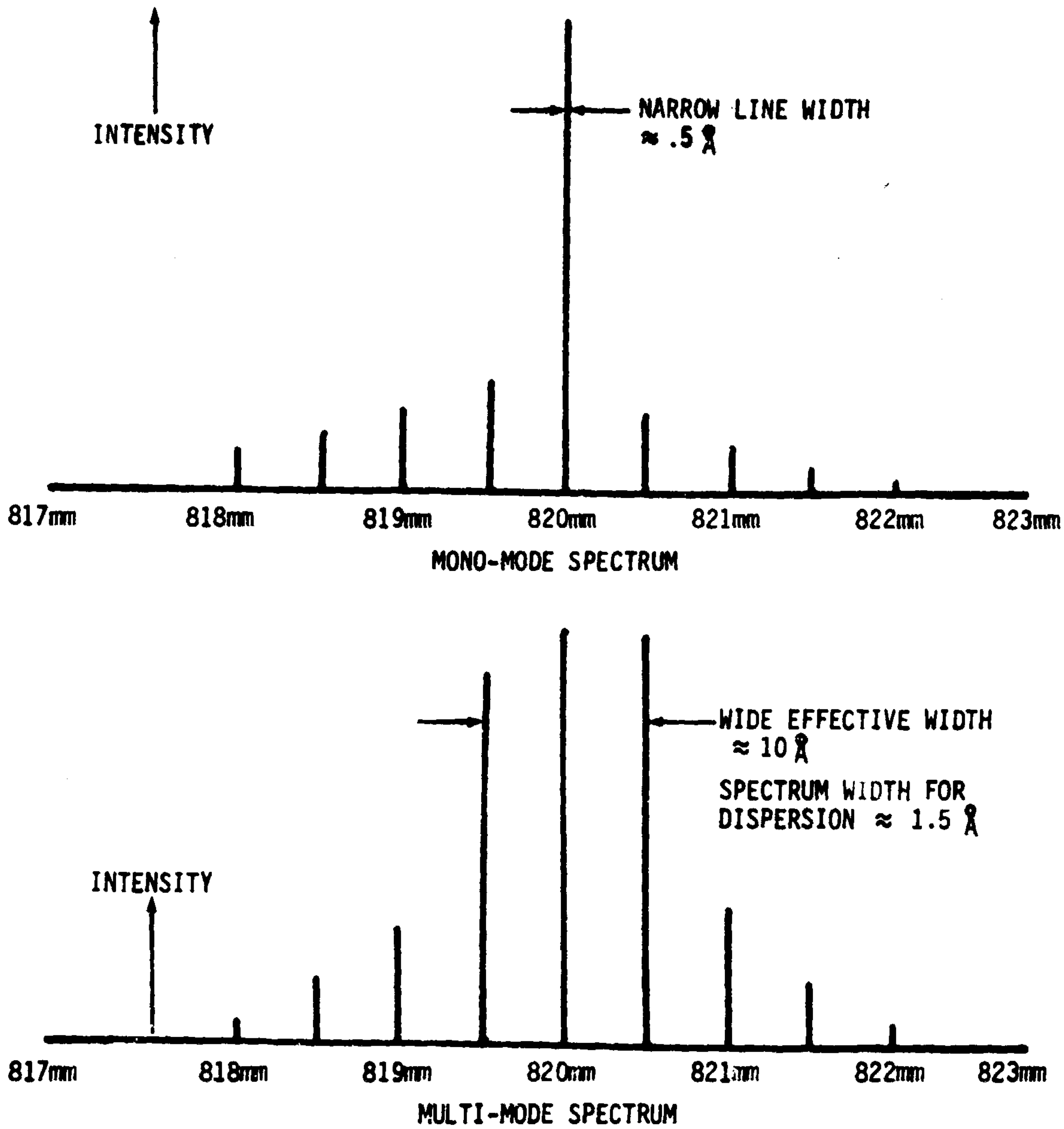


FIGURE 4.5 ILD STRUCTURES



SINGLE AND MULTI-MODE SPECTRUMS

FIGURE 4.6

multimode lasers in fiber optic communications. A single mode laser coupled to a multimode fiber produces an interference pattern at the end of the fiber. This will cause noise in the system, especially as the pattern is dependent on the position of the fiber/cable. Moving the fiber/cable will generate new interference patterns creating different noise problems. The line width of the spectrum is the controlling factor. A single mode laser has a very narrow spectrum. Multimode lasers have an effective line width equal to the separation of the modes. Dispersion is not a problem, being a function of the widths of all the modes. Figure 4.6 has examples of the differences between line width and mode width.

The failure modes of ILDs can be separated into two categories: mirror (or facet) failures and crystal failures. LEDs are subject only to crystal failures. Mirror failures are predominantly of two kinds: drastic and erosion. Drastic mirror damage is caused by overdriving the laser. This is the type of failure encountered when the device is subjected to current spikes. The mirrors themselves are formed by cleaving the crystal along bond lines (much like with jewels) and are also known as facets. The power density is extremely high at the facets. Even in normal operation the power densities are around 1.0 MW/cm. When subjected to a current spike, the power output (and density) increases several times and literally blows the facet off the diode crystal. This is not a problem in operation as long as the maximum power ratings are not exceeded.

Erosion of the facets is a very slow process. The mirror, during use, tends to deteriorate. The mirrors are necessary for the diode to operate as a laser. The deterioration reduces the efficiency of the devices and power begins to drop. A facet, properly passivated, should last between $10^5 \rightarrow 10^6$ hours before deterioration has reduced the power output to unacceptable levels.

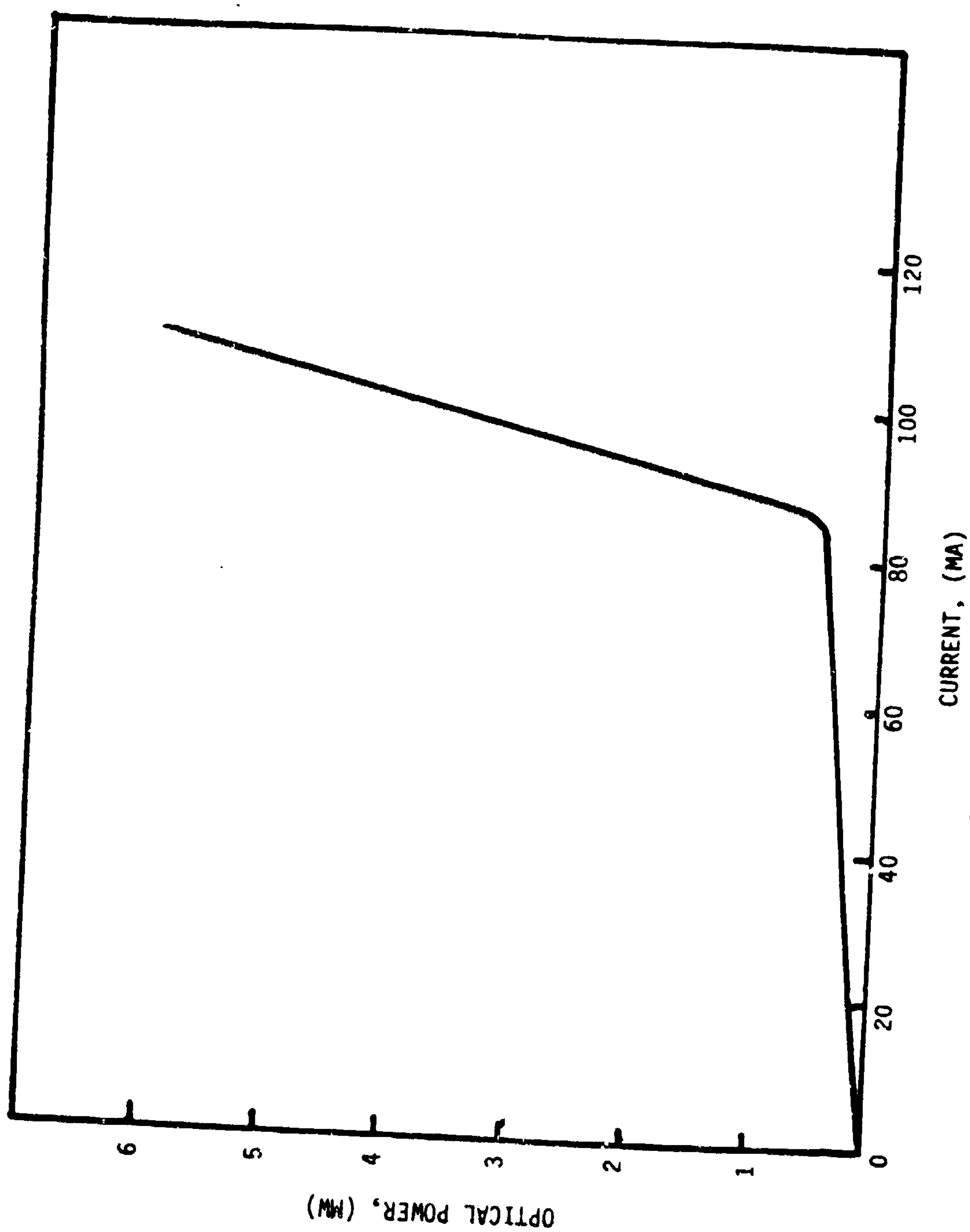
One theory proposed to explain the cause of erosion sees the process as a photochemical reaction. At the moment of cleaving, the molecules of the facet become very active. Carbon and oxygen molecules become bonded along the facet for a depth of approximately 50Å. The photochemical reaction rate between these molecules and the crystal is power density dependent. Above a power output of about 5 mw, the reaction rate will sharply increase while below this power the reaction rate remains constant. If this theory is correct, then operating the diodes at high power levels will speed up the rate of erosion. This theory is not universally accepted yet and is offered only as a possible explanation of the process.

The other failure mechanisms are crystal related and are common to both ILDs and LEDs. The two predominant failure modes are: dark line defects and impurity diffusion into the active region.

Dark line defects are the normal cause of failure of diodes which have short (a few hundred hours on down) lifetimes. Defects in the crystal form nonradiative centers where light is not produced. These centers tend to grow and congregate into what is known as dark lines. As the dark lines grow, more of the drive current flows through the centers, reducing the efficiency of the diode (more current is needed to produce the same amount of light). These defects can be screened by burn-in tests. The diodes are normally run for 100 to 200 hours. The power output is compared between the start of the test and the end. If the output has dropped below a certain percent (which varies among manufacturers), the diode is rejected.

Impurity diffusion into the active region is a failure mode common to all ICs. It is also known as bulk degradation. The efficiency of the devices slowly drops, reducing the power output (per constant current). It is uncertain whether bulk degradation or facet erosion is the dominating factor in ultimate ILD life. In either case, a properly made and operated diode should operate for 10^5 to 10^6 hours. Notice should be taken that lifetimes are in terms of operating time as opposed to shelf time. The degradation occurs only while the device is in operation.

Laser diodes are threshold devices. After a certain value of drive current, the output efficiency will dramatically increase. The point at which this increase occurs (the lasing threshold) varies from device to device (even from the same manufacturer). Manufacturers normally supply a plot of output vs. drive current for each diode. An example is shown in Figure 4.7.



ILD, OPTICAL POWER VS CURRENT

FIGURE 4.7

Although no one reported running radiation tests, it appears that laser diodes are not as susceptible to radiation damage as other ICs. Laser diodes were used in a recent nuclear detonation test. They were the only component which survived the test. One possible explanation involves the fact that the active region of an ILD is buried inside the diode and that the surrounding crystal provides some protection.

4.2 Connectors

Table 4.3 is a summary of the connector data analysis. Fiber optic connectors available today cover a very broad range from simple single contact fiber bundle or plastic fiber types to multicontact types capable of handling bundles, single fibers, and conventional wires in the same shell. At present, there is no released military or industrial standard for a fiber optic connector although they are in preparation. Test specifications for nearly all parameters and environmental stresses have been developed by the EIA P6.4 committee and a generic specification to IEC standards has been prepared by the EIA P6.3 committee. These documents are in various stages of review at present but should be available some time in the 1981 time frame. Detail specifications for connectors will be written as needed under the generic format.

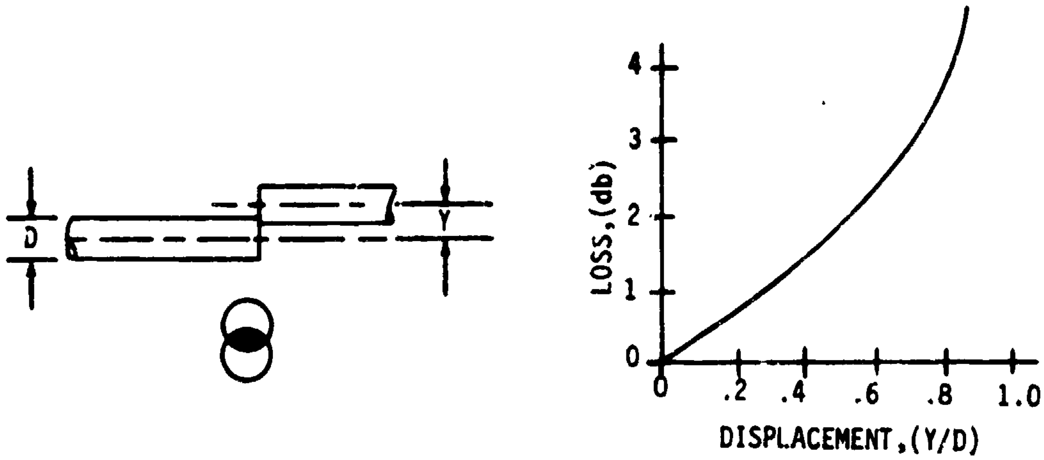
The connectors available today can be classified broadly into commercial/industrial and military types, the distinction being the capability of withstanding the so-called military environment rather than being a military qualified part. As the latter are of major importance, they will be the type discussed. Parameters of primary importance to connector performance include fiber alignment, protection, cable strain relief, size, and cost.

Fiber alignment is the prime consideration in the determination of connector transmission characteristics. Alignment is normally broken down into lateral, axial, and angular modes, as shown in Figure 4.8. With the telecommunications fibers used today with core diameters of from 50 to 65 microns (2 to 2-1/2 mils), a few tenths of a mil (10% core diameter), lateral misalignment will cause greater than 1/2 a db loss, a 1° angular misalignment will cause 1/3 of a db loss, and a 10% of core diameter end separation will cause a 1/4 db loss. The

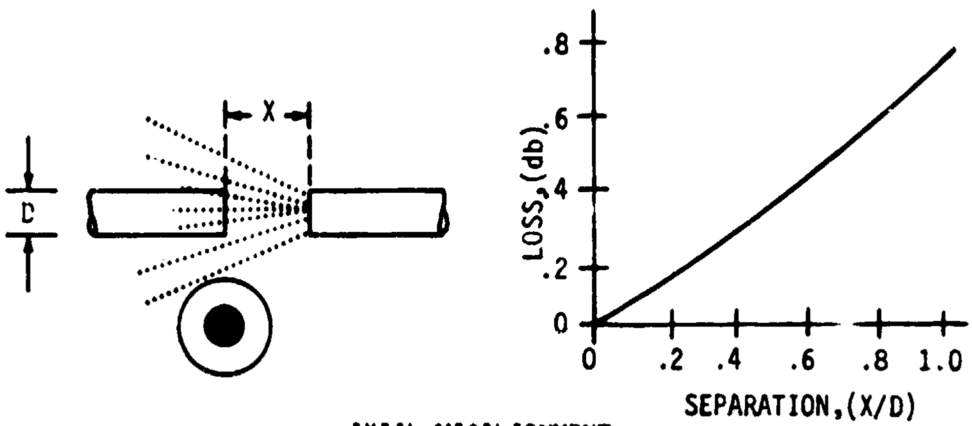
COMPONENT: CONNECTORS (SINGLE TERMINATION, MULTITERMINATION)

SUITABLE FOR CURRENT SPACE USE:	YES (WITH SUITABLE ADHESIVES)
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 CURRENTLY BEING GENERATED
SPACE QUALIFICATION:	1982 (IF REQUIREMENTS ARE DEFINED)
APPLICATIONS:	CONNECTIONS BETWEEN FIBER OPTIC COMPONENTS AND OPTICAL FIBERS.
FAILURES MODES AND MECHANISMS:	CONTAMINATES (SERIOUSLY IMPAIRS COUPLING EFFICIENCY) ADHESIVES FAILURE (BOND BETWEEN FIBER AND CONNECTOR FAILS UNDER ENVIRONMENTAL STRAIN).
LIMITATIONS:	DEVICES NOT DEVELOPED TO MIL/SPACE LEVELS DUE TO LACK OF MARKET AND LARGE EXPENSE. REQUIREMENTS SPECIFIC TO FIBER OPTIC CONNECTORS NEED TO BE DEFINED.

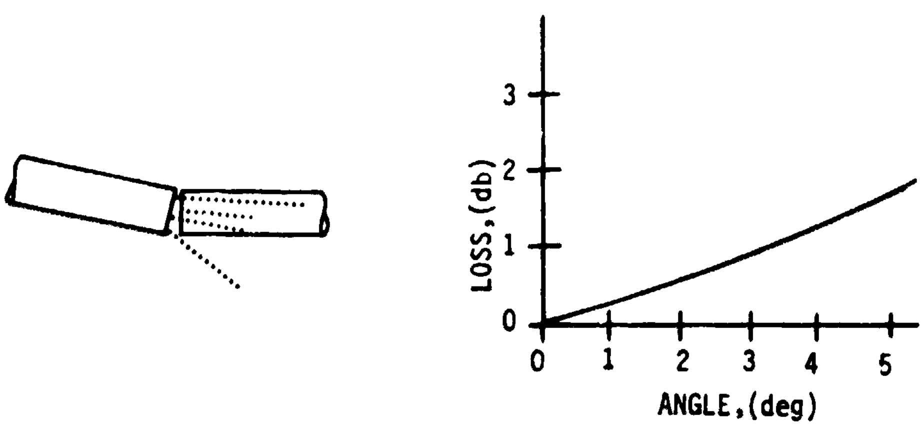
TABLE 4.3 CONNECTOR ANALYSIS



LATERAL MISALIGNMENT



AXIAL MISALIGNMENT



ANGULAR MISALIGNMENT

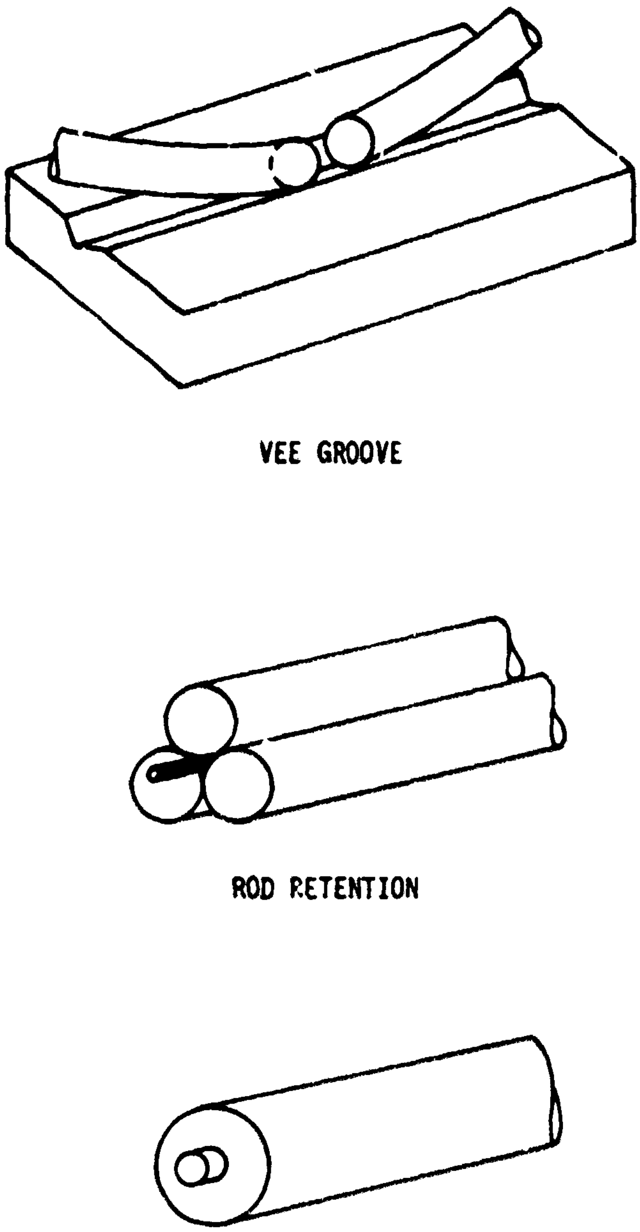
MISALIGNMENT LOSS

FIGURE 4.8

above losses are also dependent upon fiber numerical aperture (NA). They are approximately correct for NAs of about .3 and will be higher for higher NAs, lower for lower NAs. The above misalignment allowances represent typical values and show that extreme precision is required in connector design, manufacture, and assembly to assure low connector losses. Use of large core fibers (100μ to 200μ) can ease the tolerance problem and cut connector costs but a larger core size increases the radiation cross section of the fiber. This is a tradeoff to be considered. It should also be noted that the above losses do not include the fiber/fiber interface losses that are common to the fibers themselves. These include fresnel loss, core diameter variation loss, end surface irregularity loss, and NA variation loss. These losses generally contribute 0.2 to 0.3 db to the overall connector loss. Alignment methods used in multimode single fiber cable connectors vary from manufacturer to manufacturer. The major concern being to hold the lateral alignment and end spacing. Some of the more popular methods include placing the fiber in the space between three or four precision rods or spheres, constraining the fibers to a vee groove, use of a precision hole drilled in the termination, and use of a lens to focus the beam from separated fibers. Figure 4.9 shows examples. Fiber positioning in the alignment mechanism is done primarily with an epoxy adhesive. Because of temperature cycling and moisture problems encountered in the use of epoxies by several manufacturers alternate methods are being studied and implemented for fiber retention. These include crimping of the fiber using a soft metal ring and use of end pressure to hold fibers in place.

Strain relief of the fiber and cable is of prime importance but is often overlooked in connector design, especially in multicontact connectors. Not only must the fibers be supported axially to prevent tension fracture but laterally as well to prevent shear. The connector cable interface is particularly prone to damage because of the ability to bend the cable at right angles to the connector at this point. Use of cable stiffeners or a heat shrinkable outer sheath at this point can eliminate this problem.

The terminating portion of the connector on at least one half of the connecting pair must have some provision for movement to allow the mating of the two



VEE GROOVE

ROD RETENTION

PRECISION CONCENTRIC HOLE

FIBER ALIGNMENT METHODS

FIGURE 4.9

terminations to the tolerances required. This movement must be such that it is restrained after mating and the mated position is not affected by outside stress.

The connector must protect the fiber mating surfaces from contamination both in the mated and unmated condition and, therefore, should be of the hermetic type and should be provided with a form of dust cover or cap.

Connector cost at present is quite high due to low volume production and high engineering and fabrications costs because of the tight tolerances required. Two solutions to this problem are standardization leading to higher volume production and a decrease in tolerance requirements made possible by usage of larger core fibers.

4.3 Fibers/Cables

A summary of the data analysis on fibers and cables is given in Tables 4.4 and 4.5. Optical fiber and cable manufacturers, for the most part, have not been addressing the military/space market. The commercial market is large enough now that there is little incentive for companies to develop mil/space spec fiber and cables.

Cables are available which will meet specific mil/space requirements. However, no cable currently available will meet all the requirements. Companies are reluctant to spend their own money in this development. A commonly expressed desire was for government-funded development of fiber optic cables.

Cabling companies felt that standardization of cable structures is premature at this time. See Figure 4.10 for examples of current structure. It is felt that structure standards will hamper development. The companies also felt that currently available structures are not optimal. The fact that full mil/space qualifiable cable is not available would tend to support this. A frequently used example was the attempt to buy cable for use in a cruise missile. The concensus of opinion was that the stated requirements for the cable were unrealistic. They felt that many of the tolerances were too tight and that, overall, the require-

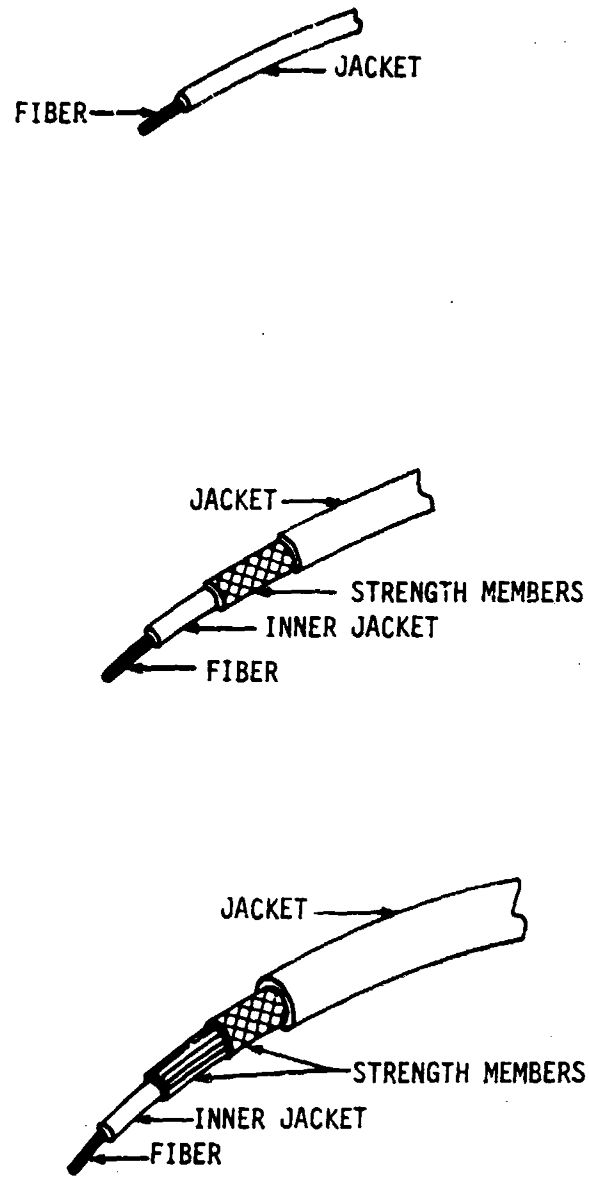
COMPONENT:	CABLE
SUITABLE FOR CURRENT SPACE USE:	YES (WITH ATTENTION TO TEMPERATURE CYCLING)
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY BEING GENERATED)
SPACE QUALIFICATION:	1982 (IF REQUIREMENTS ARE DEFINED)
APPLICATIONS:	PROTECTION OF OPTICAL FIBER FROM HOSTILE CONDITIONS.
FAILURE MODES AND MECHANISMS:	BREAKAGE KINKING (PHYSICAL DAMAGE TO FIBER) OUTGASSING
LIMITATIONS:	CABLES ABLE TO MEET SPECIFIC MIL/SPACE REQUIREMENTS BUT NOT ALL REQUIREMENTS CONCURRENTLY. REQUIREMENTS SPECIFICALLY OF FIBER OPTIC CABLES NEED TO BE DEFINED.

TABLE 4.4 CABLE ANALYSIS

COMPONENT: OPTICAL FIBER

SUITABLE FOR CURRENT SPACE USE:	YES
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY IN DEVELOPMENT)
SPACE QUALIFICATION:	1982 (IF REQUIREMENTS ARE DEFINED)
APPLICATIONS:	LOW TO HIGH DATA RATE TRANSMISSION. SUITABLE FOR AREAS CLOSED TO ELECTRICAL WIRING. HIGH EMI, EMP AREAS. LOW BER.
FAILURE MODES AND MECHANISMS:	BREAKAGE OF FIBER.
LIMITATIONS:	TEMPERATURE EXTREMES. SOME FIBER TYPES MORE RADIATION RESISTANT THAN OTHERS. RESISTANT TO ADHESIVES USE.

TABLE 4.5 FIBER ANALYSIS



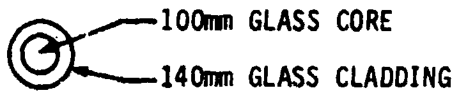
CABLE STRUCTURES

FIGURE 4.10

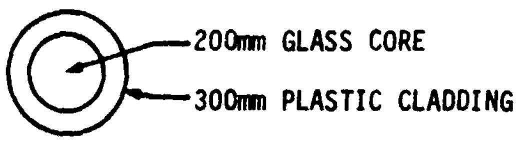
ments were overengineered. All the companies that talked about this contract indicated that they were not going to bid it. It was felt they could not meet requirements for the stated price of the (fixed price) contract. Apparently, if full mil/space cable is needed, then a set of requirements need to be developed and a government-funded development program to achieve the requirements will be needed.

Due to its two desirable features, plastic clad silica fiber (PCS) was concentrated on during discussions. PCS is naturally more radiation resistant than other fiber types. Larger core diameters are possible with PCS, as compared to glass on glass, due to the more flexible nature of the plastic cladding. A larger core makes for increased coupling at the source (LED, ILD) and for lower connector losses. See Figure 4.11 for fiber types. However, PCS does have several problems: it is sensitive to moisture, the attenuation dramatically increases at low temperature, and terminations are difficult due to the soft nature of the plastic cladding. Moisture and low temperature sensitivity are material related problems. Moisture would be absorbed into the cladding, changing its properties and increasing fiber attenuation. Cold temperature is a problem in that the index of refraction of the plastic cladding would change at low temperatures. The change in the index of refraction would affect the numerical aperture of the fiber, causing it to become smaller. This limits most PCS fiber to operating in temperatures higher than -20°C.

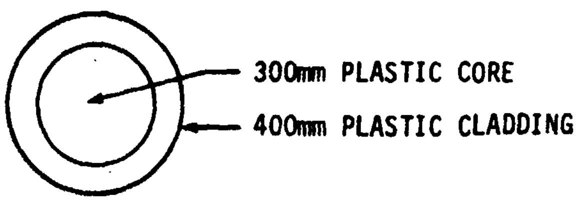
The core of the fiber, being harder than the cladding, tends to migrate in and out at the end of the termination under various fiber load conditions. This is also a problem during polishing of the termination. Under polishing, the core would be compressed into the cladding so that when polishing was completed, the core tended to extrude beyond the end of the connector. This made it very susceptible to damage and repeated connections would often destroy the polished end, causing an increase in connector loss. Suitable adhesives which could grip the plastic cladding and the metal connector are not available and the fiber end could change its position relative to the connector under handling or installation. The use of the replaceable cladding at the fiber end as well as the modified connectors have solved these problems. It should be noted that the connectors used (modified) are not necessarily the best suited for space applications. However, it is significant that a solution has been developed.



GLASS ON GLASS



PLASTIC CLAD SILICA



PLASTIC CLAD PLASTIC

OPTICAL FIBER TYPES

FIGURE 4.11

Although the companies surveyed were in the process of developmental work on PCS, only one company reported being able to operate in temperatures as low as -60°C. This same company (Company Q) has also addressed the termination problem. Essentially, they remove the soft plastic cladding at the very end of the fiber, replacing it with a harder material of similar optical properties. They have also modified commercially available connectors to compensate for other termination limitations.

4.4 Detectors

A summary of detector data analysis is found on Table 4.6. None of the companies interviewed had bad things to say about fiber optic detectors. This technology appears to be the most highly developed area of fiber optics. The detector chips are very durable and should last as long as other silicon diodes. There were no reported failures of detector diodes in any working systems. The only precaution necessary for safe operation is not to exceed the reverse bias maximum rating of the diodes.

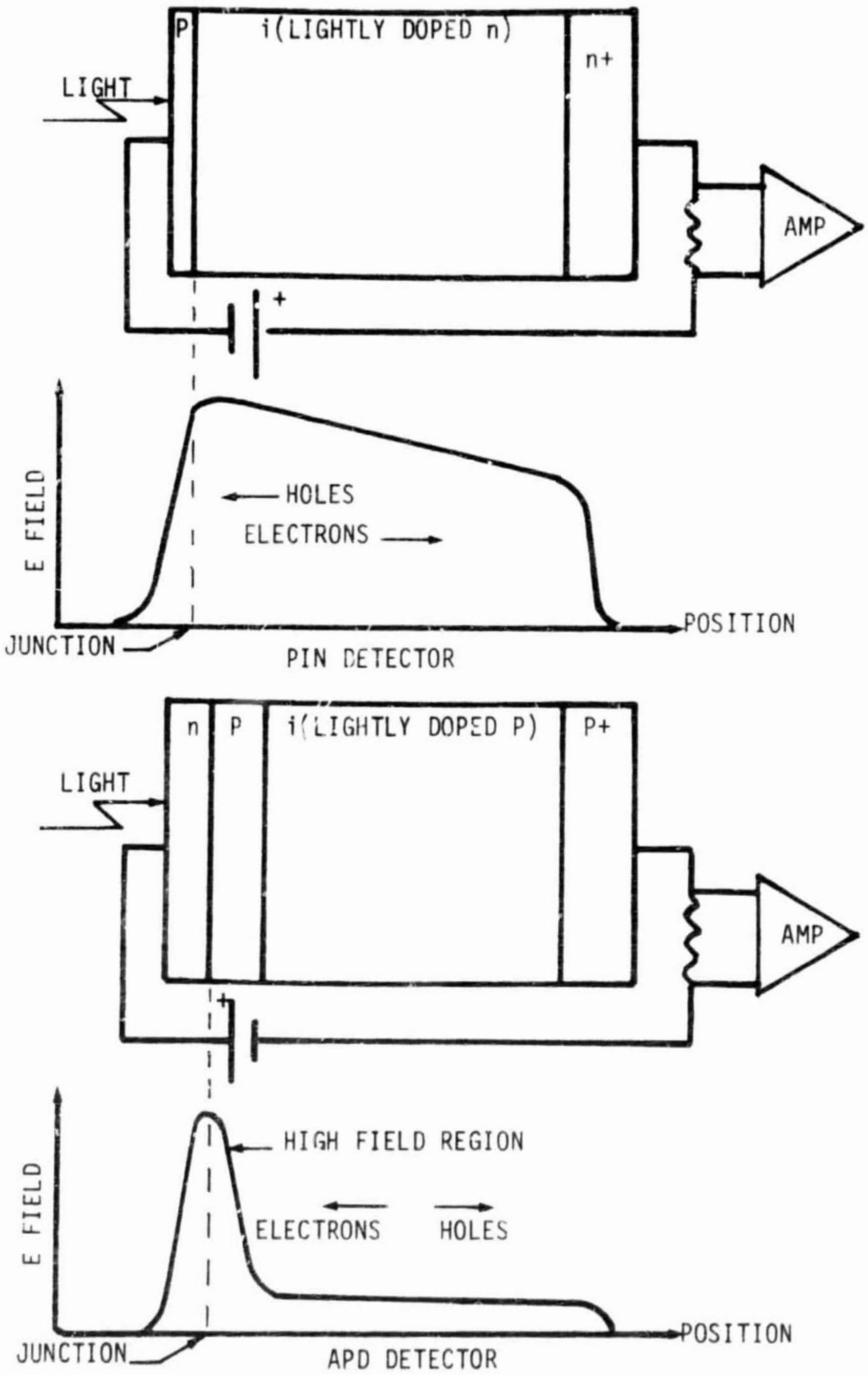
In order to work at peak speed, detector diodes need to be reverse biased. For example, a certain PIN diode has a rise and fall time of 300 ns under zero bias conditions. The application of 20V of reverse bias will reduce the rise and fall time down to only 1 ns. Diodes which possess this fast a response time and are sensitive to light in the frequency range of interest (800 nm to 950 nm) will, of necessity, cost more due to their more complex structures.

PIN diodes consist of three regions: a P and an N region separated by what is known as the intrinsic (I) region, as shown in Figure 4.12. The intrinsic region is necessary for trapping and converting the photons into hole-electron pairs. The longer the wavelength, the further the photon will penetrate into the silicon before forming a hole-electron pair (minority carriers), as shown in Figure 4.13. For example, 80% of the photons at 910 nm will be absorbed after penetrating 65 μm into the silicon, while for 800 nm the 80% penetration depth is only 15 μm.

COMPONENT: DETECTORS

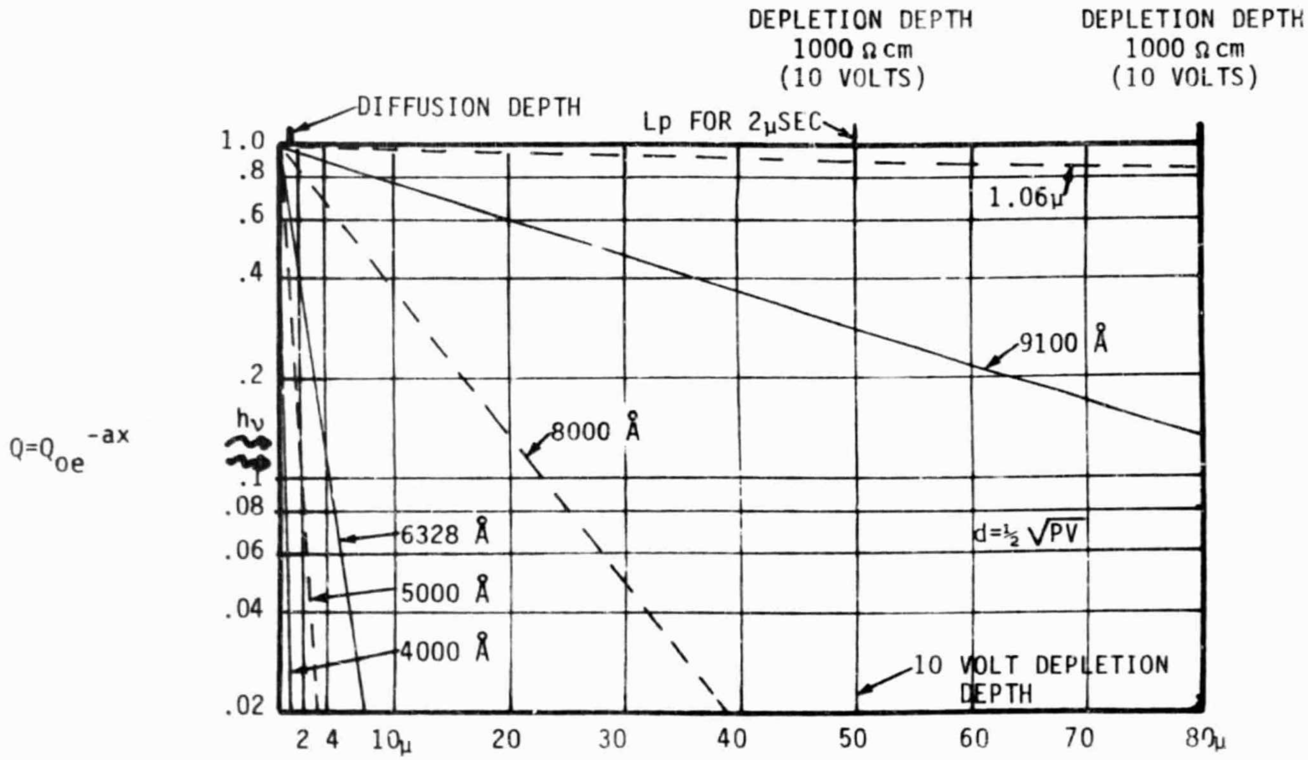
SUITABLE FOR CURRENT SPACE USE:	YES
RELIABILITY:	.1%/1000 HRS
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY BEING GENERATED)
SPACE QUALIFICATION:	1982
APPLICATIONS:	ALL FIBER OPTIC LINKS
FAILURE MODES AND MECHANISMS:	ELECTRICAL OVERSTRESS. OPTICAL OVERSTRESS (EXTREMELY HIGH LEVELS NEEDED, UNLIKELY IN A FIBER OPTIC LINK)
LIMITATIONS:	PACKAGING IS NOT CURRENTLY OPTIMAL. APD'S GAIN TEMPERATURE AND VOLTAGE DEPENDENT. SILICON DETECTORS GOOD OUT TO 850→900NM WAVELENGTHS

TABLE 4.6 DETECTOR ANALYSIS



PHOTODIODE STRUCTURES

FIGURE 4.12



A plot of the absorption of light in silicon at differing wave lengths. Also shown are a typical diffusion depth of 1 micron for a planar diffused photodiode structure, a typical minority carrier diffusion length in n-type silicon of 50 microns, and depletion depths of 50 microns and 80 microns for applied voltages of 10 and 25 volts respectively, for P/N junctions formed on 1000 ohm cm n-type base silicon. Distance from the front surface into the silicon is represented on the abscissa, from left to right. Fall off light produced charge density is represented along the ordinate reading from top to bottom. From reference 20.

ABSORPTION OF LIGHT IN SILICON

FIGURE 4.13

Therefore, to make a detector with a broad spectral sensitivity, a thick intrinsic region is needed. However, the response time for the diode is dependent on the transit time of the electron/holes to travel from their point of origin to the electrodes on the P and N regions. This means that a thick intrinsic region (with a higher spectral range) will have a slower response time when compared to thin intrinsic region detectors.

The lifetime of the minority carriers depends on the purity and perfection of the silicon crystals used. Impurities and imperfections will cause lower collection efficiencies, increased leakage current, higher noise levels, and shorter lifetimes. The conclusion is that performance directly relates to reliability. The silicon PIN photodiodes currently available have been developed to a high degree. Detection is possible down to the levels where thermal noise is the limiting factor.

Avalanche photodiodes (APDs) are also rather well developed. Their more complex structures are generally more expensive than PIN diodes, however, their two big advantages may compensate for added costs. APDs are faster and more sensitive than PIN diodes. APDs have internal gain when strongly reverse biased. The internal gain allows an increase in the dynamic range of the system of 10 dB or more. This could be of major importance in designing a data bus system where the high loss of the multiport coupler precludes the use of a PIN diode. Reverse biases of 200 to 400V are common. The high reverse bias also creates a stronger electric field in the diode which reduces the response time. (APDs have been used for detection well into the gigahertz region.) The gain of APDs is temperature dependent. If used in an environment of temperature fluctuations, a compensation circuit is necessary. However, in the stable conditions of space, such a circuit may be superfluous.

The relationship between performance and reliability appears to be true also for APDs. The same factors (crystal perfection and low impurity levels) which limit the lifetime of the diodes are also largely responsible for noise and lakeage. None of the companies talked to indicated any problems with APDs.

In contrast to the high degree of development of the photodiode chip is the poor packaging typically used. The chips are normally mounted in a modified transistor/diode package (such as a TO-18). While this allows a hermetic seal, it greatly increases the coupling losses incurred when terminating a fiber. Figure 4.14 is an example of the problem. The active area needs to remain small to keep the junction capacitance low. This allows the diode to be used in high speed electronic circuits.

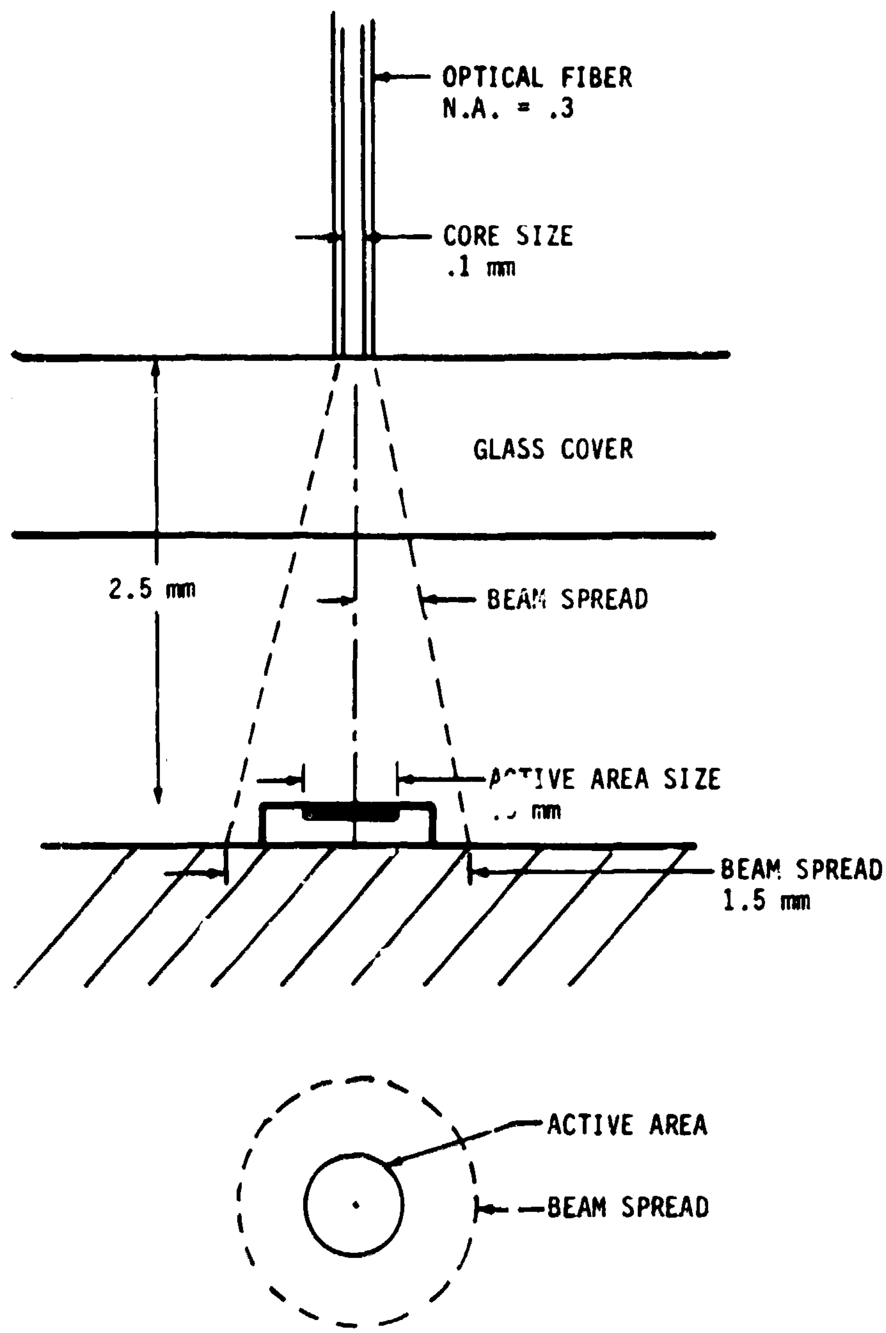
The solution used to date has been to reduce the separation between the end of the fiber and the active area. This has been accomplished by pigtailing a fiber or other optical waveguide directly to the chip. This is done at the expense of losing the hermetic seal. Lenses are also used to increase the coupling. Use of lenses requires a high degree of mounting accuracy. Although it can be done, it is rather expensive.

A better solution is the use of an integral optical waveguide, as shown in Figure 4.15. This approach is being used/studied by some companies. The waveguide can be quite large compared to the incoming fiber size. The active areas of chips are often in the 500 μm diameter size while the core diameter of the military standard short haul fiber is 100 μm. An optical waveguide with a core diameter of 300 μm could be mounted to the chip surface. The coupling loss between the waveguide and the surface would be low. Also, use of a large core would insure a low loss between the waveguide and incoming fiber as one of the main loss mechanisms of connectors, axial misalignment, would be eliminated.

In order to develop such a device to mil/space requirements, more development in adhesives would be required. As was further discussed under connectors, adhesives are not available which will satisfy all requirements. Another problem to be addressed is entire package hermeticity.

4.5 Fiber Optic Transmitter/Receiver Modules

Table 4.7 contains a summary of the transmitter/receiver modules data analysis. There is a large variety of fiber optic modules on the market. Most are designed



BEAM ≈ 9X ACTIVE AREA
COUPLING LOSS ≈ 10 dB

TYPICAL PACKAGING PROBLEM

FIGURE 4.14

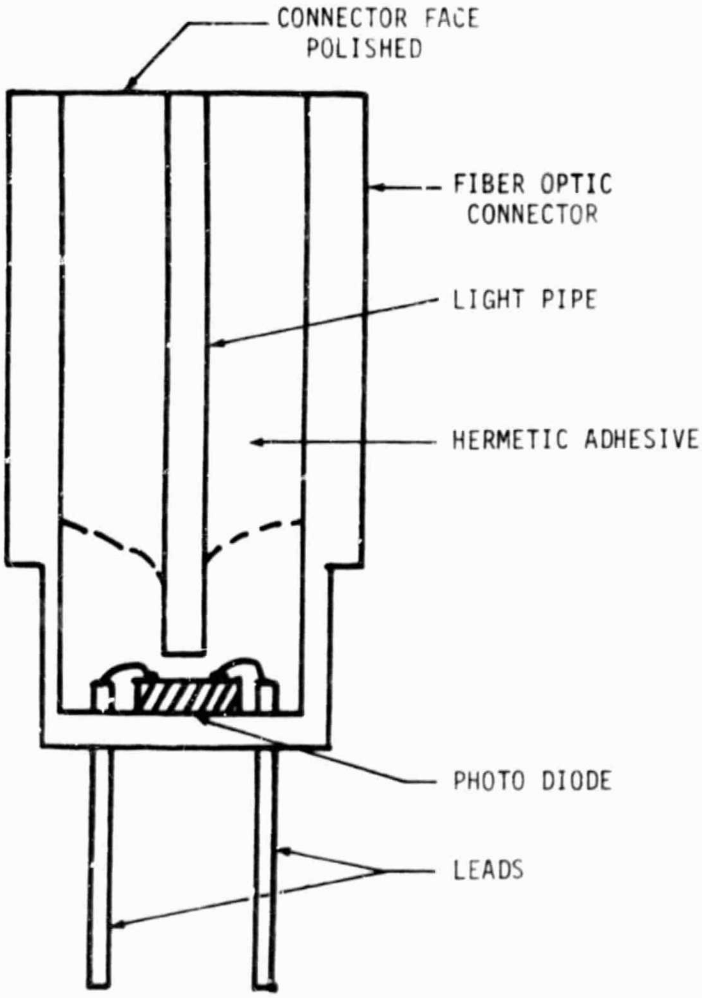


PHOTO DIODE PACKAGE WITH INTEGRAL OPTICAL WAVEGUIDE

FIGURE 4.15

COMPONENT: MODULES

SUITABLE FOR CURRENT SPACE USE:	NO
RELIABILITY:	2%/1000 HRS
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY BEING GENERATED)
SPACE QUALIFICATION:	MODULES NOT NORMALLY CONSIDERED FOR SPACE APPLICATIONS
FAILURE MODES AND MECHANISMS:	SUSCEPTIBLE TO FAILURES COMMON TO SOURCES, DETECTORS, IC'S, AND CONNECTORS
LIMITATIONS:	LOW DATA RATES ($<$ 10MHz). ENVIRONMENTAL LIMITATIONS (NONHERMETIC, TEMPERATURE RANGE)

TABLE 4.7 FIBER OPTIC MODULES ANALYSIS

for the commercial market although a few companies claim their modules will meet military specifications with the exception of the LED. One set of modules was designed under an Air Force contract.

The function of the modules is to be the interface between the electronics and the optical fiber. A typical transmitter module will contain an LED and the associated electronics necessary to drive it. The receiver module will be comprised of a photodiode and the electrical circuitry needed to translate the optical signal into an electrical signal. Usually, all that is necessary to operate the module is a supply voltage and an input (or output for the receiver) of the signal. Figure 4.16 shows a typical module.

Although no hard reliability data is currently available, the modules appear to be very reliable with only a few failures being reported. Many companies involved in the manufacturing of the modules are currently starting reliability studies and reliability data should be available in several months.

One major problem with the modules is their packaging. They incorporate epoxy seals, especially around the input/output connectors. This normally limits operating temperatures to the 0° to 70°C range and does not provide true hermetic seals. One company reported being able to produce a military version incorporating a hermetically sealed and screened LED with high reliability integrated circuits.

4.6 Couplers

A summary of the analysis on the coupler data is on Table 4.8. Couplers are a necessary part for use in data buses. A main disadvantage of fiber optics compared to conventional electrical wiring is the difficulty in splitting up the signal. This will be very important in space applications in interconnecting computers, sensors, controls, and other systems (such as communications). At present, almost all fiber optic links are point-to-point systems, one output to one input. To increase the flexibility and utility of fiber optics, the ability to transmit one output into several inputs (or vice versa) will be necessary.

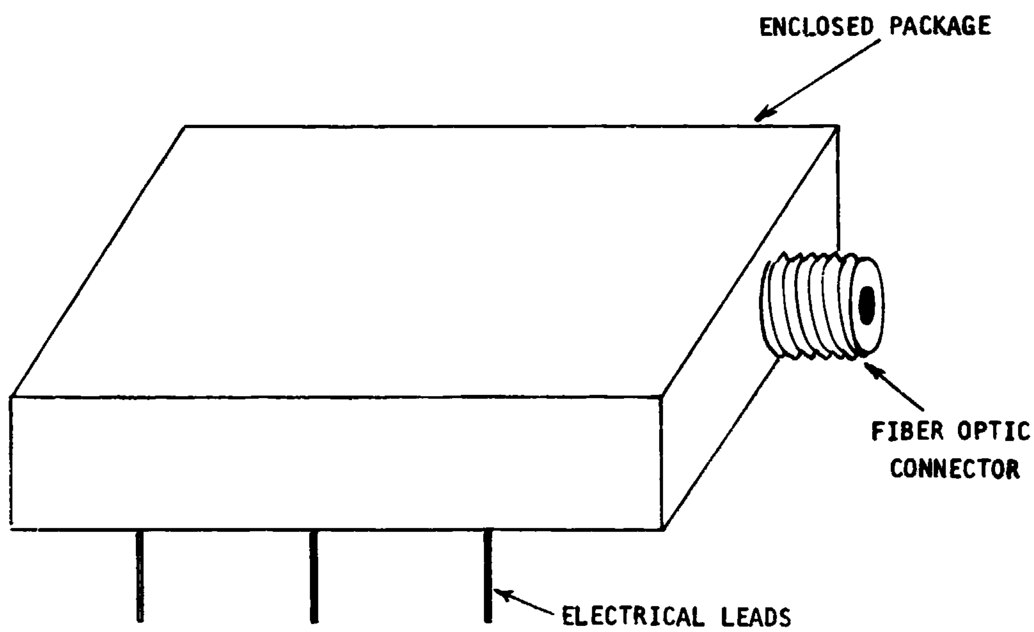


Figure 4.16 Fiber Optic Transmitter and Receiver Modules

COMPONENT:	COUPLERS
SUITABLE FOR CURRENT SPACE USE:	NO (DEVELOPMENT IN PROCESS)
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 (BEING GENERATED)
SPACE QUALIFICATION:	1983
APPLICATIONS:	DATA BUS REQUIREMENTS FOR USE IN FIBER OPTIC COMMUNICATION SYSTEMS
FAILURE MODES AND MECHANISMS:	INSUFFICIENT DATA
LIMITATIONS:	INPUT LOSSES ARE TOO HIGH. DYNAMIC RANGE OF OUTPUT TOO LARGE. DEVICES ARE BULKY AND FRAGILE.

TABLE 4.8 COUPLER ANALYSIS

Currently available couplers are simply not adequate. They are too lossy and have environmental limitations. No company interviewed was satisfied with the couplers. Consistency and repeatability are also a problem.

The usual multiport (star) coupler is normally a series of fibers stacked into a small array and butt joined into a mixing rod. The opposite end of the mixing rod either terminates in a similar array of fibers (in a transmissive coupler) or a highly reflective surface (in a reflective coupler). Figure 4.17 shows an example of each type.

Another kind of coupler used for small number terminations (normally two in and two out) employs fused fibers. Two fibers are fused together by heating them. Surface tension forms the fused end into a circular shape. The fused end is then cut and/or polished and joined to another similarly formed fiber pair as shown in Figure 4.18.

New coupler types are being developed by several companies. The companies, however, were reluctant to describe their work and no details are available.

4.7 Test Equipment

A summary on the data analysis on test equipment is found on Table 4.9. The development of test equipment is hampered by the lack of standards. Most manufacturers of fiber optic devices/systems have built their own test equipment. As such, it is very hard to compare devices/systems of different manufacturers as each uses their own test methods. One manufacturer of ILDs stated that adequate test equipment was available if you knew what to look for. Hopefully, the introduction of testing standards will alleviate the problems of each manufacturer testing by their methods on their test equipment.

The testing of active devices such as LEDs or APDs can be split into three sections: optical, electrical, and mechanical/environmental. The electrical and mechanical/environmental tests are performed as for any other semiconductor device. Standard test equipment and procedures are used. The optical testing or test equipment is not yet standardized. Parameters that are normally checked for

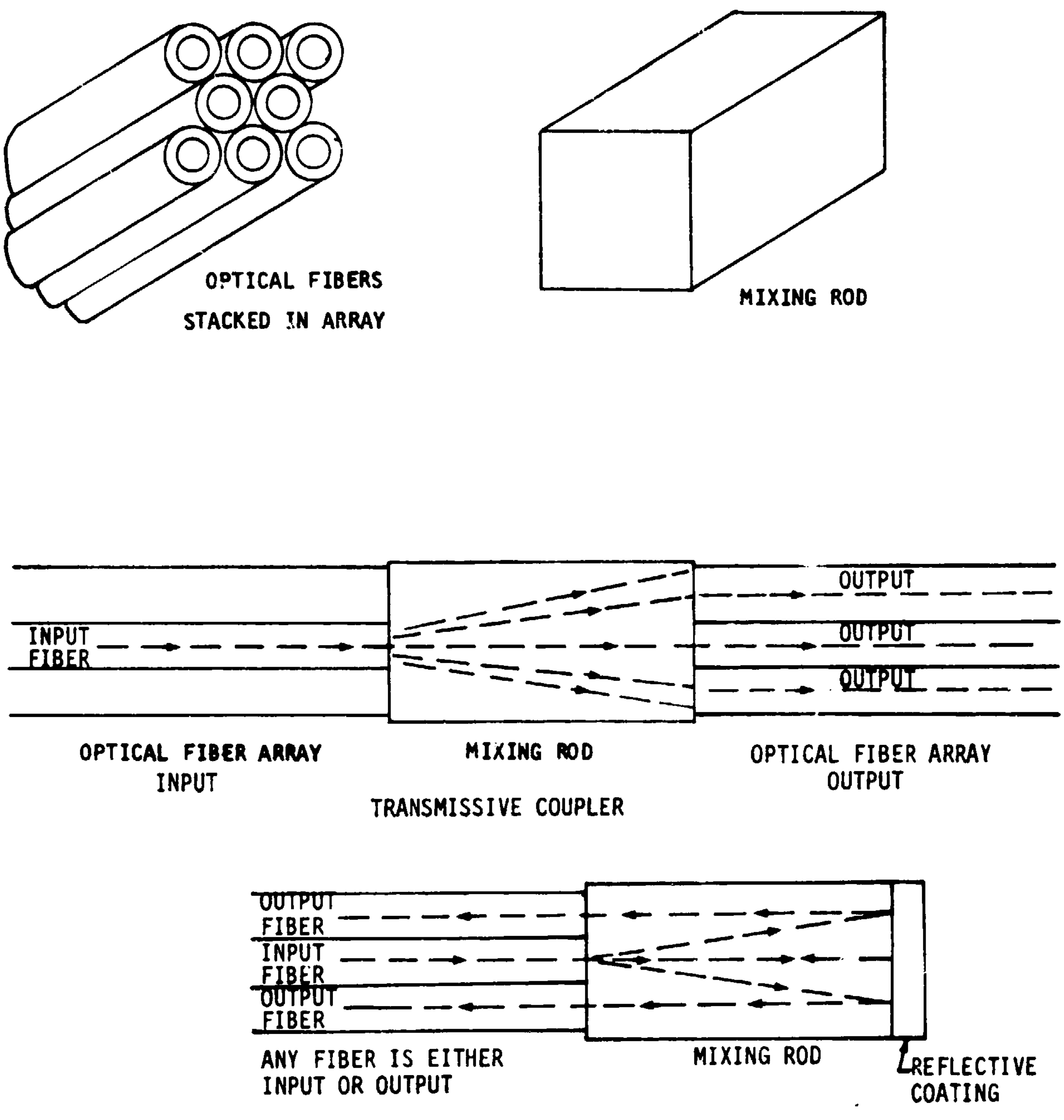
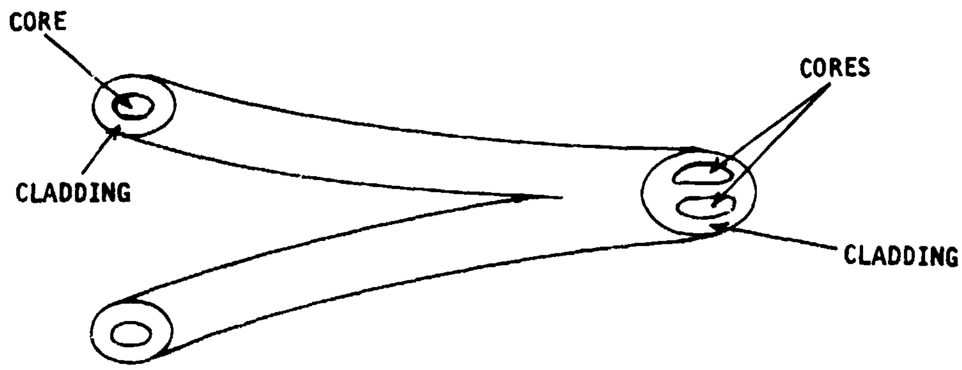
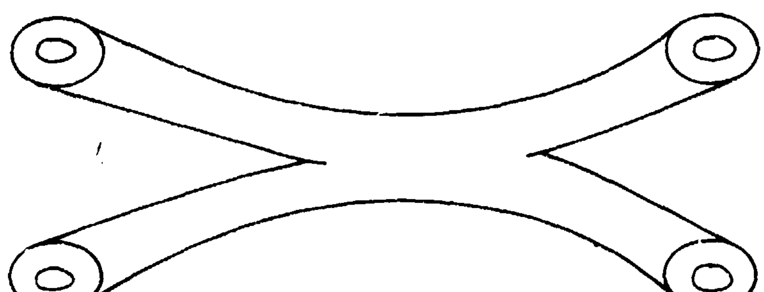


FIGURE 4.17 MULTI-PORT COUPLER STRUCTURE



TWO OPTICAL FIBERS FUSED TOGETHER



FUSED COUPLER

FIGURE 4.18 FUSED COUPLER STRUCTURE

- LACK OF TESTING STANDARDS IS A PROBLEM
- MOST COMPANIES BUILD TEST EQUIPMENT IN HOUSE
- FIELD TEST EQUIPMENT IS ADEQUATE BUT NOT OPTIMAL
- MOST AVAILABLE EQUIPMENT IS EXCESSIVELY EXPENSIVE

TABLE 4.9 TEST EQUIPMENT SUMMARY

sources are power output, radiation pattern, and spectrum. For detectors, responsivity, spectral response, and directional sensitivity are normally tested and specified.

For optical fibers, optical testing has been standardized but test equipment has not. Optical properties normally specified include attenuation vs. wavelength, bandwidth, and numerical aperture (NA). Cables are tested for mechanical and environmental performance.

Testing of systems is normally performed first in the factory and again after installation. The most commonly used systems tests is bit-error rate (BER). Standard equipment and procedures are used. The installed cable is also tested. Tests of attenuation and bandwidth are normally performed. (Bandwidth is a limiting factor only for long runs at high data rates.)

Most of the test equipment manufactured is for fiber measurements. A very well designed photometer is available. Several of the companies interviewed admitted that it was one of their standard pieces of test equipment. Although primarily designed for measurement of light levels out of fibers, use of an integrating sphere would make it practical for measurement of LEDs and ILDs. The manufacturer has plans for this modification. Integrating spheres are necessary for accurate measurement of the light output of LEDs and ILDs due to their wide beam spread. This particular photometer is highly accurate (traceable to NBS), easy to use, field usable, and low in cost.

The other primary piece of fiber test equipment is the Optical Time Domain Reflectometer (OTDR). In operation it is similar to electrical time domain reflectometers. A short optical pulse is transmitted down the fiber. Light reflecting back from flaws, breaks, connectors, or even Raleigh back scattering is detected, converted into electricity, and displayed on an oscilloscope. Figure 4.19 shows the basics of the OTDR. Their greatest use is in determination of breaks or faults in the optical fiber, especially after it has been installed. Primarily developed for long communication lines such as CATV or telecommunications they possibly will have little use for installations in space born equipment where the link lengths will be relatively short.

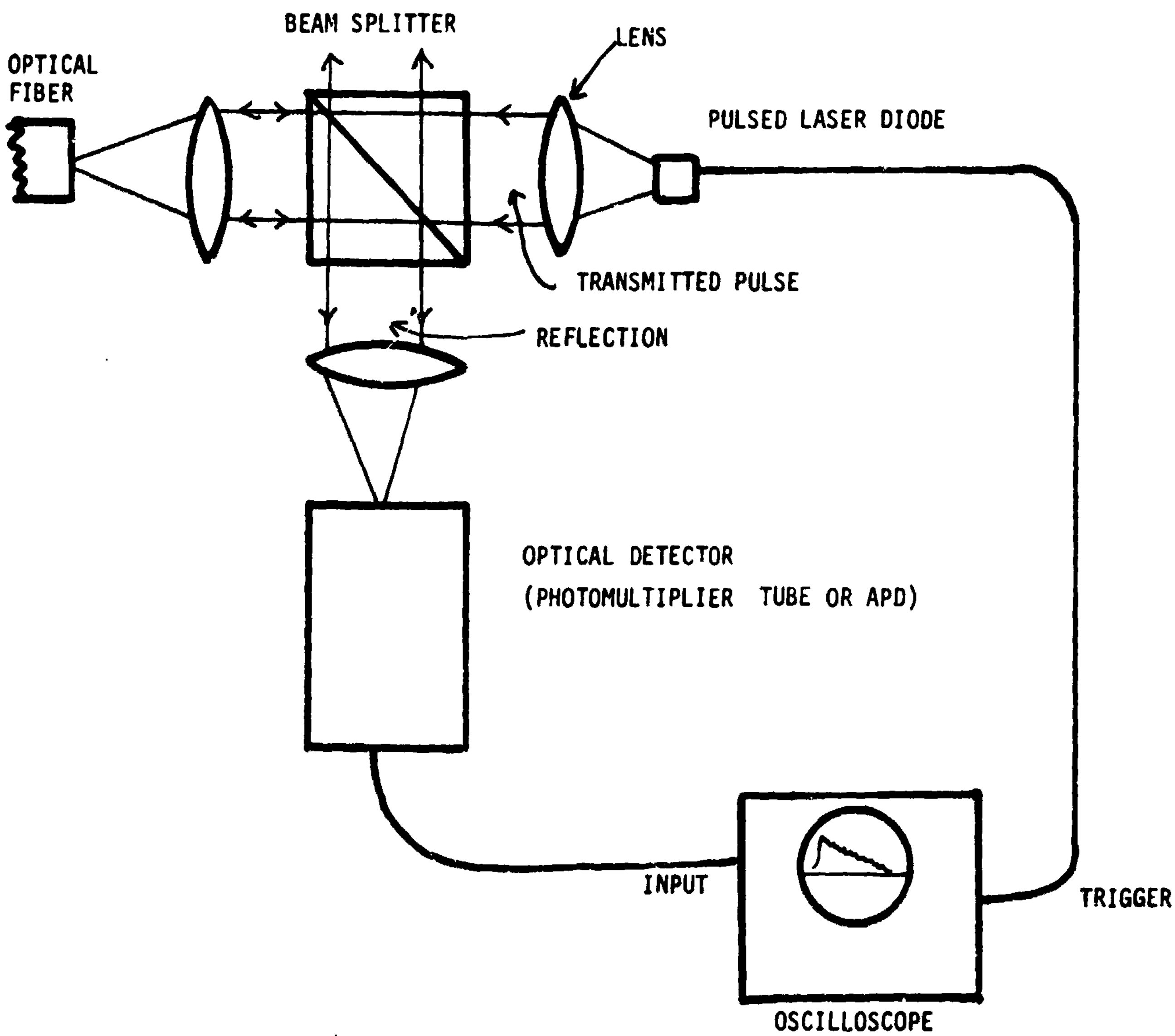


FIGURE 4.19 OPTICAL TIME DOMAIN REFLECTOMETER

Many fiber optic companies feel that the OTDR still needs to be further developed. They are still very expensive and people have complained about the repeatability and accuracy of the measurements (although the repeatability and accuracy problems may be with the oscilloscope instead of the OTDR).

More test equipment is sure to be developed once testing standards are decided on. Experience with existing equipment (often described as adequate but not good) will lead to further refinement as problems are identified.

4.8 Government/Industry Committees

All major government/industry committees were surveyed to determine the present state of standardization effort. Specific industrial committees contacted included EIA, SAE, AIA, IEEE, and IEC. Governmental and quasi-governmental agencies and committees contacted included DESC, NATO, NOSC, NAVAIR, NUSC, NAEC, CORADCOM, NASA, and the tri-services committee on standardization. The majority of the activities at present are centered upon the P.6 committee of the EIA. This committee is currently developing generic specifications for fiber optic splices, connectors, couplers, repeaters, sources, detectors, fibers, cables, and cable assemblies plus test specifications for connectors and fibers and a glossary of fiber optics. This work is being closely coordinated with DESC in order to provide documentation in most usable form for both government and industry. Figure 4.20 shows the organization of the P.6 committee.

As EIA is the representative of the International Electrotechnical Commission (IEC) for the United States, all documentation is available to this group (IEC) for world standards through EIA personnel represented on the IEC SC-46E committee. NATO is represented through DESC personnel on that committee. In addition, members of the tri-services committee on fiber optics are members (nonvoting) on all the major EIA P.6 committees on fiber optics. IEEE is participating in the development of active device standards through representation on the P6.5 committee on transducers.

SAE through its A2-H, A2-K, and A2-X committees has and is contributing to the development of standards for cable test, data buses, and installation

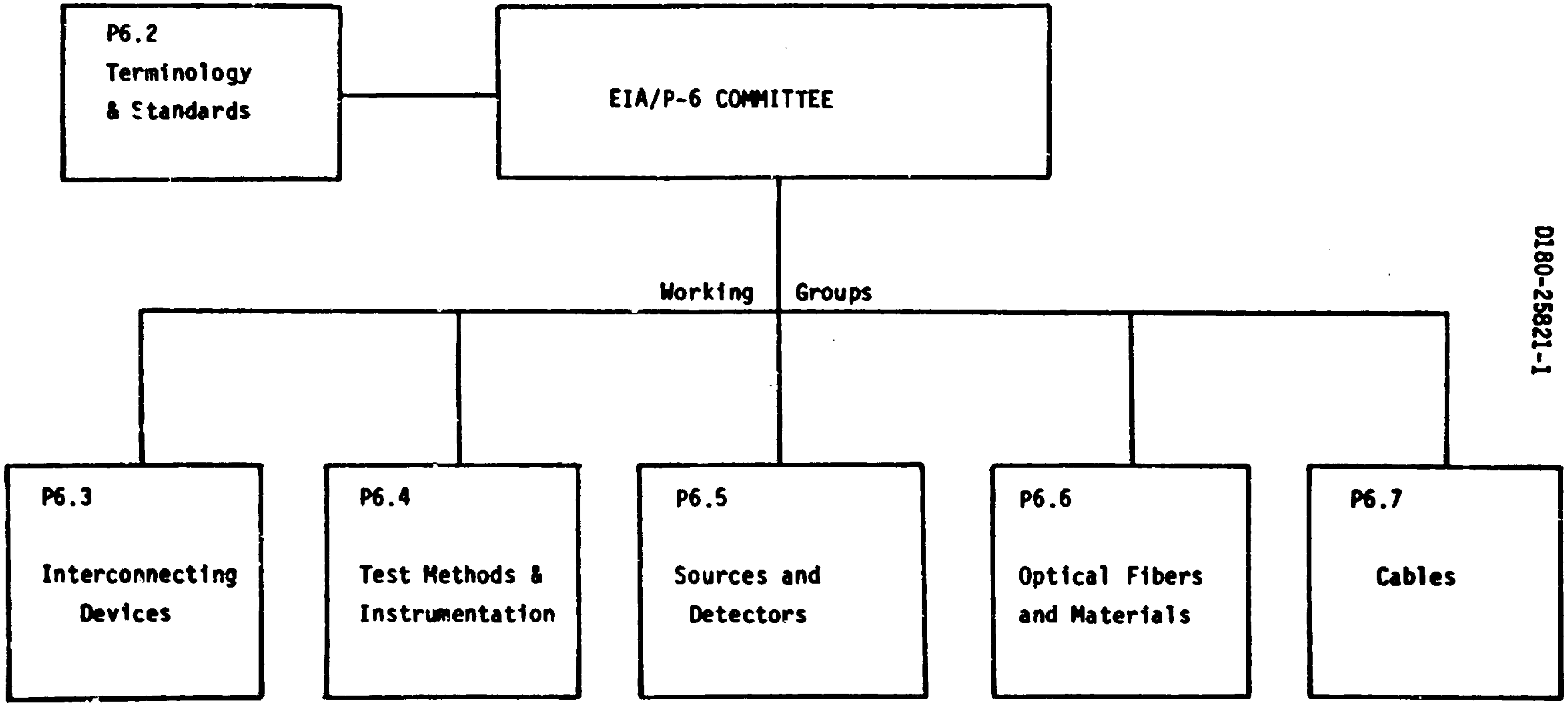


FIGURE 4.20 ORGANIZATION OF THE EIA/P-6 COMMITTEE

technology, respectively. The first document released through this effort is DOD-STD-1678 entitled "Military Standard Fiber Optics Test Methods and Instrumentation." This standard is addressed primarily to testing cables.

The information presented in the preceding paragraphs is primarily static. It is expected that because of the urgent need for the standards and specifications relating to fiber optics that the EIA and SAE will accelerate their efforts in order that first tier documentation could be completed ready for circulation in 1981. If this cannot be accomplished, the military will take steps to develop documentation outside the societies to meet their schedules.

4.9 Surveys

The surveys provided necessary but misleading background information. For example, 85% of the suppliers responded that they had reliability information. Upon being interviewed, most companies admitted they were just starting their reliability studies. No hard data was available and most reliability information was based on development tests or extrapolated from incomplete lifetime tests.

Another misleading result is the small number of user responses. Most suppliers of systems do the installation. Also, as many of the systems are new, the suppliers maintain close contact with the users. Information on installation problems or failures can, therefore, be obtained from the suppliers.

The surveys were important in establishing the candidates for interviews and for getting an idea of the size of the industry. As is noted in the surveys, most companies are rather small, having less than 50 employees devoted to fiber optics.

A total of 27 respondents out of 49 replied to the questionnaires mailed out. (Many of the companies visited responded only at the interview.) Of the respondents, 18 were suppliers, 5 were users, and 4 test equipment manufacturers. All contact with committees was made in person or by telephone. To provide the data from each of the respondents in most usable form, a compilation of each of the form types was made and a narrative report was written. This data is presented below:

Fiber Optic Supplier Questionnaire

A total of 18 suppliers responded to the furnished questionnaire. They were divided into four different categories as follows:

Category	Responses
Sources/detectors	3
Cable/fiber	6
Connectors	5
Systems	4

As all questions were not answered by all respondents, averages were made based upon only those who did. A composite questionnaire sheet which gives totals and/or averages to the questions asked follows the narrative discussions of some of the more pertinent items.

A total of 42 items were manufactured by the 18 suppliers. The duplicate lines being primarily sources and detectors, cables and fiber, connectors and couplers, and then all the systems/assemblies.

As can be noted from the yearly quantities, quantities shipped are in the range of 3,000 to 20,000 units for components and from 10 to 2,000 for assemblies or systems. All suppliers use some standards/specifications. About 1/2 use military or industrial versions while 90% use in-house specifications as well. All used testing procedures or QA programs and only 16% expressed having any significant problems with their testing program. Roughly 85% did have some reliability data or failure information (but no hard data was made available) and felt that standardization was suitable for all components.

FIBER OPTIC SUPPLIER QUESTIONNAIRE COMPILATION

1) Fiber Optic Components Manufactured

			Yearly Quantities
A.	Sources	5	
B.	Detectors	2	
C.	Cable	8	3,000 - 20,000
D.	Fiber	3	
E.	Connectors	7	
F.	Other: ______	1	

2) Fiber Optic System/Assemblies Produced

			Yearly Quantities
A.	Couplers	5	
B.	Repeaters	3	10 - 2000
C.	Data Links	9	
D.	Systems	5	
E.	Other: ______		

3) Do you use standards/specifications? 0 No 18 Yes

10 Military
9 Industry
16 In-House

4) Do you use testing procedures or quality assurance programs to verify specifications?

18 Yes 0 No

5) Have you encountered any significant problems with your testing program?

3 Yes 14 No 2 Not Applicable

6) Do you have any reliability data or pertinent information on failure?

15 Yes 3 No

7) Which component/systems do you feel are suitable for standardization?

All

8) How many people are actively engaged in fiber optics or related activities at your facility(s)?

		Full Time Avg.	Part Time Avg.
A.	Management		
B.	Material		
C.	Quality Assurance		
D.	Engineering	34	15
E.	Technical		
F.	Support		
G.	Clerical		
H.	Other		

The number of full time people engaged in the fiber optics portion of the companies work force varied from a low of one to a high of 70, the average being 34. Part time employees averaged 15.

As the respondents included most of the industry leaders in the field of fiber optics, it can be seen that total personnel and production quantities are not really very large. This indicates that users should be in a position of leverage as far as being able to influence the development of standards to meet their requirements.

Fiber Optic User Questionnaire

A total of 5 users responded to the questionnaire and classified themselves in industrial/military classifications as their work was primarily government contract related. The applications were a mix of all choices but communications, data transfer, and security were the more often mentioned. Systems classifications were computer link, ground support, space, telecommunications, aircraft, and CATV in that order of numbers. The components purchased by all users include emitters, detectors, cables, and connectors. Sixty percent bought couplers, while 20% bought links or installed systems. The average amount spent on each of the categories ranged from $4,000 to 30,000. Growth rates were predicted by only one user but that rate was 50% annually. Eighty percent used procurement standards and of these all used in-house specs while half used military/industrial specs. It was interesting to note that while only 16% of the suppliers experienced testing problems, 80% of the users did. The average number of people employed at each user facility was 10 full time and 5 part time, about 1/3 that of the suppliers.

C-2

FIBER OPTIC USER QUESTIONAIRE COMPILATION

1) User Classification

- 3 Industrial
- 3 Military
- 2 Government Agency
- 0 Consumer

2) Applications

- 5 Communications
- 3 Control
- [illegible] Video
- 5 Data Transfer
- 4 Security

3) System Classification

- 2 Space
- 1 Aircraft
- 3 Ground Support
- 0 Marine
- 4 Computer Link
- 2 Telecommunications
- 1 CATV
- 0 Other: __________

4) Types of Components Purchased

			Quantity/Year	$ Value
A.	Emitters	5		18,000
B.	Detectors	5		6,000
C.	Cable	5		30,000
D	Connectors	4		4,000
E.	Couplers	3		20,000
F.	Repeaters	0		
G.	Data Links	1		5,000
H.	Installed Systems	1		
I.	Other:			

5) Expected Growth Rate in $/Year

			50%	80	81	82	83	84
A.	Emitters							
B.	Detectors							
C.	Cable							
D.	Connectors	All	1					
E.	Couplers							
F.	Repeaters							
G.	Data Links							
H.	Installed Systems							
I.	Other:							

6) Do you use procurement or design standards/specifications for these items?

__1__ No   __4__ Yes

__1__ DoD
__1__ Industry
__4__ In-House

7) Do you use inspection or qualification testing to verify specifications?

__3__ Yes   __2__ No

8) Do you use a maintenance program for servicing equipment in the field?

__2__ Yes   __2__ No

9) Do you have reliability data or pertinent information on part failures?

__4__ Yes   __1__ No

10) Have you encountered any testing problems?

__4__ Yes   __1__ No

11) Have you encountered any installation problems?

__2__ Yes   __2__ No

12) How many people are actively engaged in fiber optics or related activities at your facility(s)?

	Full Time	Part Time
A. Management		
B. Material		
C. Quality Assurance		
D. Engineering	10	5
E. Technical		
F. Support		
G. Clerical		
H. Other: ______		

13) Company Name: ______
Principle Products: ______
Number of Employees: ______
Business Volume: ______
Company Address: ______
Telephone: ______

14) Principle Contacts:

Management: ______
Engineering: ______
Quality Control: ______
Material: ______

Test Equipment Questionnaire

Four test equipment manufacturers responded to the questionnaire and represented 12 items of fiber optic test and assembly equipment. All companies furnished accuracy data on their products as well as calibration period. All the items except one optical power meter was field usable, i.e., portable battery operated. Half the companies did have testing problems with their product. The average size of the companies was small; 5 full time, 5-1/2 part time employees. The quality of the equipment and the employee skill level, as reflected from the plant visits, were quite high.

TEST EQUIPMENT QUESTIONNAIRE COMPILATION

1) List test equipment you manufacture for fiber optics.

   12 items

2) What is the reliability of the readings of your equipment?

3) Do you verify its reliability? __4__ Yes __0__ No

4) Which of your equipment is field usable?

   12 field usable
   1 not portable

5) Do you plan to adapt your equipment to field use? _____ Yes _____ No

6) Did you encounter any significant testing problems? _____ Yes _____ No

7) How many people are actively engaged in fiber optics or related activities at your facility(s)?

	Full Time Avg.	Part Time Avg.
A. Management		
B. Material		
C. Engineering		
D. Technical	5	5-1/2
E. Quality Assurance		
F. Support		
G. Clerical		
H. Other		

8) Comapny Name: ____________________

   Principle Products: ____________________

   Number of Employees: ____________________

   Business Volume: ____________________

   Company Address: ____________________

   Telephone: ____________________

9) Principle Contacts:

   Management: ____________________

   Engineering: ____________________

   Quality Control: ____________________

   Material: ____________________

5.0 DETAILED CONCLUSIONS OF THE ANALYSIS

Based upon the data collection and analysis, several conclusions can be drawn relative to fiber optic standardization, reliability, and application.

5.1 Applications

The applications of fiber optics to NASA current and future programs include virtually all aspects of data transmission, communications, and control and even has limited use in power transmission. Implementation has been limited primarily by lack of qualified hardware, economics, need of optimized components for specific applications, inconclusive reliability data, relatively little design experience, no standards, and lack of installation and maintenance technology. Fiber optics will be used increasingly as the advantages of this technology become forcing functions. These advantages include high bandwidth, EMI/EMP immunity, nonnecessity for return paths, size-weight-volume reduction, radiaton resistance, longer distances between repeaters and lower cost.

Current applications where fiber optics can be used to advantage include long line telecommunications networks, television transmission, data transmission, and signal transmission. Particular advantages of Fiber Optics in these applications include bandwidth, transmission distances, size, security, and cost (see Figure 5.1). Future applications include aircraft and spacecraft where the high bandwidth, low size-weight-volume and EMI/EMP immunity will be drivers.

To properly scope the application areas of fiber optics, some of its major disadvantages should be discussed. One of these major disadvantages, of course, is the relative difficulty of interconnection. Compared to the ease of soldering, crimping, or twisting conventional electrical conductors together, the splicing of two fibers into one is a fairly complicated task and the joining of more than two without a coupling device is a virtual impossibility. Connecting devices available today are expensive, have high losses, are complicated to assemble, and do not provide adequate cable/end protection when compared to conventional wire connectors. Multiport couplers and power tapping systems when compared to something like an ordinary transformer are crude, inefficient, and

CURRENT

- DATA LINKS IN AREAS OF:
  - HIGH NOISE
  - NONCONSTANT ELECTRICAL GROUND
  - LOW BIT-ERROR RATE REQUIREMENTS
- TELEPHONE LINKS IN AREAS OF:
  - HIGH DATA RATE REQUIREMENTS
  - LONG DISTANCE BETWEEN TERMINALS
  - SMALL SIZE REQUIREMENTS (CABLES)

NASA FUTURE

- SPACE-BORN LINKS
  - MULTIPORT DATA BUSSES
  - POINT-TO-POINT DATA LINKS
- GROUND LINKS
  - RADAR TO STATION
  - STATION TO STATION
  - COMPUTER INTERLINKS
- ADVANTAGES
  - HIGH BANDWIDTH
  - NOISE IMMUNITY
  - RADIATION RESISTANCE
  - LOWER WEIGHT
  - LOW BIT ERROR RATE

FIGURE 5.1 POTENTIAL APPLICATION AREAS

costly. In practically all fiber optics applications, the signal must be converted from electrical to optical at transmission and vice versa at reception. Considering nothing else, this conversion means extra power loss and more hardware and increased cost.

In view of the merits and disadvantages in the use of fiber optics, where and when should NASA use this technology today and in the future? Specifically, the area today where the technology is cost effective is when we need noise-free, wide bandwidth transmission. This area includes:

Digital data transmission
Analog signal transmission
Remote system command and control

Future applications when high parts reliability and quality is known should include:

Space platform data buses
Space platform point-to-point links
Interconnection between integrated optic systems

Each application will have unique parameters associated with the considerations of the environment of the application, the bandwidth required, and the length of the line need to be considered. A summary of the envisioned application parameters are on Table 5.1.

5.1.1 Parts Limitations

While there are no qualified parts per se presently available for use in space or by the military, it is felt that qualified systems can be constructed using selected available parts. The rationale behind this statement is based upon the experience of several space vehicle manufacturers in prototype systems, using state-of-the-art components.

APPLICATION	TEMPERATURE	BANDWIDTH/ DATA RATE	LENGTH	STYLE	RADIATION	COMMENTS
COMPUTER/COMPUTER INDOOR	+10^{0}C - +30^{0}C	10MHZ	>100M	POINT TO POINT (DUPLEX)	NONE	GOOD APPLICATION FOR PLASTIC FIBER & CONNECTORS ON SHORT RUNS LED SOURCES
COMPUTER/COMPUTER OUTSIDE	-20^{0}C - +50	10MHZ	>2KM	PT. TO PT. (DUPLEX)	NONE	CAN USE BURRUS DEVICES STEP INDEX FIBERS
LONG LINE COMMUNICATIONS	-20^{0} - +50^{0}	300MHZ	>12KM	PT. TO PT. (DUPLEX)	NONE	MAY REQUIRE REPEATERS GENERALLY USE ILD'S & APD'S PLUS GRADED INDEX FIBER GOOD APPLICATION FOR SINGLE MODE
SPACE PLATFORMS SMALL	TEMPERATURE CAN BE CONTROLLED	300MHz TO GHZ	>100M	PT. TO PT. OR DATA BUS	LONG TERM (DEPENDS ON MISSION)	DATA BUS REQUIRES COUPLERS RADIATION MAY REQUIRE SPECIAL FIBER SELECTION
SPACE PLATFORMS LARGE	TEMPERATURES EXTREMES DEPEND ON MISSION	300MHz TO GHZ	MED 100M	PT. TO PT. OR DATA BUS	LONG TERM (DEPENDS ON MISSION)	EMI ON SPACE POWER PLATFORMS, RADIATION AND TEMPERATURE CAN BE A PROBLEM
WEAPONS PLATFORMS	-55 TO +125^{0}	200MHZ	>100M	PT. TO PT. OR DATA BUS	EXTREME NUCLEAR DEVICES	HIGH PULSE RADIATION FROM ATTACKING WEAPONS SYSTEMS MAY CONTAIN INTEGRATED OPTICS - MIGHT REQUIRE SINGLE MODE FIBERS

TABLE 5.1 APPLICATION PARAMETERS

One of the prime reasons, of course, for lack of qualified parts is the lack of qualification criteria, standards, and specifications. While the criteria may not be documented for all fiber optic components, it is known or can be obtained from experience gained on other related space qualified hardware by several companies and agencies working in this technology as shown in Table 5.2. Generic specifications and standards can be developed now to provide the component requirements and to define test methods. The major difficulty to avoid is to prevent locking in on outdated parts which are qualified and have detail specifications while newer high technology parts are available but have not yet been qualified. The other extreme of constant design update and qualification of parts is certainly not cost effective, either in terms of design change costs or proliferation of device types. A middle road must be found which will not stifle use of improved technology devices yet which will provide the necessary controls to provide the quality and reliability needed and to prevent unnecessary proliferation.

The more mature components, ready for immediate use, include the hermetically sealed PIN detector diodes. These devices may be obtained from several vendors in different sizes and packages (mostly T.O. style). While the package configurations are not optimum as far as optical power coupling efficiency, they are certainly usable. Optimum high frequency response generally will require use of a physically small device so that generally a tradeoff must be made between speed and coupling efficiency. Pigtailed devices available today are generally not truly hermetic but could be used in some applications.

Because optical sources share the same packaging technology as that used for optical detectors, the same limitations as far as coupling and hermeticity hold. In addition, power vs. temperature phenomena require that either device temperature be controlled or that optical power be monitored in order to maintain output power levels. In addition, for some devices, notably ILDs, temperature and/or output power must be controlled to insure design life.

While the components used in fiber optic cables, i.e., the fibers, buffers, strength members, and jackets, are such that they can operate in a space environment, combinations of these materials are not always compatible over the temperature and other stress ranges encountered in space applications. Temperature coefficient mismatch is a common problem. Also there is variation of refractive index with temperature. The major concern, of course, is the effect of radiation. Plastic clad silica, at present, is the most promising material combination for this problem but suffers in that, in most cases, it has temperature (cold end) limitations and is difficult to terminate because of lack of concentricity and movement of the core in the cladding. Temperature coefficient differentials between fiber and strength members can be compensated for, in some cases, by use of glass strength members rather than the more common kevlar.

Interconnecting devices can be a major problem in any fiber optic application. There are many connectors now on the market that when matched with designated cables and with correct inserts can provide a low loss interconnect. There are few devices which can provide hermeticity, strain relief, full mil spec (-55°C to 125°C) temperature range operation, high reliability, and long life in a rugged environment. These problems are being worked by many of the major connector manufacturers and, if proper selection of components is made, a usable interconnect system can be assembled. Connector types available include the single contact SMA, the liquid lens, vee groove or rod positioning types, jeweled bearing, and precision drilled hole types. Multicontact connectors are becoming available using several of the above alignment principles. All the above mentioned are available for multimode single fiber cables. Single mode connectors are not yet available as a commercial product. Table 5.2 summarizes the findings.

5.1.2 Component Selection

A series of fiber optic components suitable for space applications is provided in Tables 5.3 to 5.8. Specifying a particular cable or connector is a more difficult problem. Most cables are made on a custom basis. Any of the vendors listed on Table 5.9 should be able to provide a cable based on the application requirements.

NASA GRADE 2 REQUIREMENTS	COMPONENT CAPABILITY (°C)				USABLE RANGE OF AVAILABLE COMPONENT
	SOURCE	DETECTOR	FIBER/CABLE	CONNECTOR	
TEMPERATURE -55°C TO +125°C	LED -55 +70 ILD -40 +50	-55 +125	-55 +125	-55 +125	LED -55 +70 ILD -40 +50
TEMPERATURE CYCLING -65 +150	-65 TO +150	-65 TO +150	-20 TO +70	-20 TO +70	-20 +70
SHOCK 1500G .5MSEC	1500G .5MSEC	1500G .5MSEC	1500G .5MSEC	1500G .5MSEC	1500G .5MSEC
VIBRATION 20-2000Hz 20G PEAK	20-2000Hz 20G PEAK	20-2000Hz 20G PEAK	20-2000Hz 20G PEAD	20-2000Hz 20G PEAK	20-2000Hz 20G PEAK
OPERATING LIFE 1000 HRS @ 125°C	LED TO +70 ILD TO +50	1000 HRS @ 125°C	1000 HRS @ 125°C	1000 HRS @ 125°C	LED TO +70 ILD TO +50

TABLE 5.2 DETAILED REQUIREMENTS

	STRENGTH	TEMP LIMITS	TCE *	ABRASION RESISTANCE	COMMENTS
ARIMID	HIGH	250°C 6% STRENGTH	4X SILICA & NEGATIVE	GOOD	HIGH STRENGTH/ WEIGHT RATIO
SILICA	VERY HIGH	1000°C	MATCH	POOR	BRITTLE
METAL	HIGH	LOW	POOR MATCH HIGH POSITIVE	GOOD	AN ELECTRICAL CONDUCTOR

* TEMPERATURE COEFFICIENT OF ELONGATION WITH RESPECT TO SILICA

TABLE 5.3 CABLING MATERIALS, STRENGTH MEMBERS

	ABRASION RESISTANCE	FLAME RETARDENCY	FLEXIBILITY	TEMPERATURE RANGE (°C)	SOLVENT RESISTANCE	COMMENTS
PVC (PREMIUM)	GOOD	EXC	GOOD	-55 - 105	POOR	SUITABLE FOR INSIDE USE LOW COST
HYTREL	GOOD	POOR	GOOD	-40 - 105	EXC	
TEFZEL 280	EXC	EXC	FAIR	-70 - 180	EXC	WILL SODA STRAW IF BENT
HALAR	EXC	EXC	FAIR	-70 - 165		
KYNAR	EXC	EXC	FAIR	-55 - 175	EXC	
POLYURETHANE	EXC	POOR	EXC	-50 - 80	GOOD	SOME TYPES WILL PASS MOST FLAME RETARDENCY TESTS
HYPALON	EXC	GOOD	GOOD	-30 - 105	POOR	
NYLON	EXC	POOR	POOR	-40 - 170	EXC	POOR RESISTANCE TO MOISTURE ABSORPTION

TABLE 5.4 CABLING MATERIALS, JACKETING

FIBERS

VENDOR PT #	TYPE	TEMP RANGE	BANDWIDTH	COMMENTS
MAXLIGHT 200-B	PCS	-40 TO +150	24MHz-KM	TERMINATION PROBLEMS BEING ADDRESSED
DUPONT	PCS	-75 TO +90	10MHz-KM	POLYMER CLADDING INSTEAD OF SILICON
CORNING 1159	GRADED INDEX GLASS	-55 TO +125	740 MHz-KM	
GALITE 6000	GRADED INDEX GLASS	-55 TO +125	740 MHz-KM	DESIGNED FOR LONG LENGTH, HIGH SPEED TELECOMMUNICATIONS MORE

TABLE 5.5 FIBERS SUITABLE FOR SPACE APPLICATIONS

	*RADIATION	BANDWIDTH	ATTENUATION	TEMPERATURE	NOTES
PLASTIC CLAD PLASTIC	300,000	20MHz-Km	300dB/Km	0^{o} - 70^{o}C	SUITABLE FOR SHORT/LOW DATA RATE LINKS
GLASS FIBER BUNDLE	3000 RADS	20MHz-Km	300dB/Km	-55^{o} TO $+125^{o}$	TECHNOLOGY BEING REPLACED BY SINGLE FIBERS
PLASTIC CLAD SILICA	ATTENUATION WILL NOT INCREASE BY 50dB	20-50MHz-Km	5-20dB/Km	-20 - +150	DIFFICULT TO TERMINATE DUE TO SOFT CLADDING. FIBERS IN DEVELOPMENT WITH LOWER TEMPERATURE RANGE (-60^{o}C)
GLASS CLAD GLASS STEP INDEX	300,000	20-50MHz-	10-20dB/Km	-55^{o} TO +125	CABLES LIMIT TEMPERATURE RANGE TO -30 TO $+65^{o}$
GLASS CLAD GLASS GRADED INDEX	400,000	1GHz	5dB/Km	-55^{o} TO +125	CABLES LIMIT TEMPERATURE RANGE TO -30 TO $+65^{o}$ RADIATION RESISTANCE VARIES
SINGLE MODE GLASS/GLASS	NO DATA	1GHz VERY HIGH	VERY LOW	-55^{o} TO	NEW TECHNOLOGY. APPLICATIONS FOR ULTRA-LONG (12Km) OR ULTRA-FAST USE (1GHz)

*DOSE REQUIRED TO INDUCE A 50dB INCREASE IN FIBER ATTENUATION FOR A 100m LINK.

TABLE 5.6 CABLING MATERIALS, FIBER CHARACTERISTICS

SOURCES

VENDOR PART NO.	TYPE	PKG	HERMETIC	TEMP RANGE	FREQUENCY RESPONSE	COMMENTS
LDL IRE-160F	BURRUS	STUD MOUNT	YES	-55 +70	TO 50MHz	PIGTAILED TO 125/150u FIBER
SPECTRONICS SD 3352	SURFACE	TO 46	YES	-20 +70	TO 50MHz	INTERNAL LENS, FOCUS SPOT 300UM
G.O. DIP DIG-830	ILD	14 PIN DIP	YES	-40 +50	1GHz	PIGTAILED TO GLASS ON GLASS FIBER

TABLE 5.7 SOURCES SUITABLE FOR SPACE APPLICATIONS

DETECTORS

VENDOR PART NO.	TYPE	PKG	HERMETIC	TEMP RANGE ^{o}C	FREQUENCY RESPONSE	NEP W/ Hz	COMMENTS
HP 5082-4207	PIN	T018W	YES	-55 +125	100MHz	5.7×10^{-14}	LARGE AREA DEVICE, HIGH 7PF
HP 5082-4205	PIN	T018L	YES	-20 +65	TO 500MHz	1.5×10^{-15}	SMALL AREA DEVICE, LOW CAPACITANCE, 0.7PF
SPECTRONICS SD 3478	PIN	T046	YES	-65 +150	50MHz	------	AVAILABLE IN AMPHENOL 905 RECEPTICAL
RCA C30902E	APD	T018 (MOD)	YES	-46 -71	TO 1GHz	3×10^{-15}	SHORT COUPLING DISTANCE, GLASS TO CHIP
TI TIED 55	APD	CL-7	YES	-----	TO 1GHz	1×10^{-12}	PILL PACKAGE
TI TIED 56	APD	TO-18	YES	-----	TO 1GHz	1×10^{-12}	NEP AT 1GHz

TABLE 5.8 DETECTORS SUITABLE FOR SPACE APPLICATIONS

TABLE 5.9 FIBER OPTIC VENDORS

CABLES

Beldon Corporation
2000 S. Batavia Ave.
Geneva, IL 60134
(312) 232-8900

Dupont Co.
Plastic Products & Resins Dept.
Willington, DE 19898
(302) 774-7850

Galite Inc.
P.O. Box 50
Wallingford, CT 06492
(203) 265-7126

General Cable Corp.
15 Prospect Lane
Colonia, NJ 07007
(201) 382-8800

ITT Electro-Optical Products Division
7635 Plantation Rd.
Roanoke, VA 24019
(703) 563-0371

Maxlight Optical Waveguides Inc.
Box 11288
Phoenix, AZ 80561

Siecor Optical Cables Inc.
631 Miracle Mile
Horseheads, NY 14845
(607) 739-3562

Times Fiber Communications
358 Hall Ave.
Wallingford, CT 06492
(203) 265-2361

VALTEC Corporation
Fiber Optics Div.
West Roylston, MA 01583
(617) 835-6082

CONNECTORS

AMP Inc.
449 Eisenhower Blvd.
Harrisburg, PA 17105
(717) 564-0101

Amphenol-Bunker RAMO
33 E Franklin St.
Danbury, CT 06810
(203) 743-9272

Berg Electronics
York Expressway
New Cumberland, PA 17070
(717) 938-6711

Deutsch Co.
Municipal Airport
Banning, CA 92220
(714) 849-7844

Hughes Aircraft Co.
Connecting Devices Div.
17150 Von Karman Ave.
Irvine, CA 92714
(714) 549-5701

ITT Cannon
666 E. Dyer Rd.
Santa Ana, CA 92702
(714) 557-4700

Trompeter Electronics
8936 Comanche Ave.
Chatsworth, CA 91311
(213) 882-1020

TRW Cinch
1501 Morse Ave.
Elk Grove Village, IL 60007
(312) 439-8900

DETECTORS

Hewlett Packard
Optoelectronics Div.
640 Page Mill Rd.
Palo Alto, CA 94304
(415) 493-1212

Motorola Semiconductor
5005 E. McDowell Rd.
Phoenix, AZ 85008
(602) 244-6900

RCA Corp.
New Holland Ave.
Lancaster, PA 17604
(717) 397-7661

TABLE 5.9 FIBER OPTIC VENDORS (Contiued)

DETECTORS (Continued)

Spectronics Inc.
830 E. Arapaho Ave.
Richardson, TX 85080
(214) 234-4271

Texas Instruments
Box 225012 MS 308
Dallas, TX 75265
(214) 234-4422

SOURCES

Bell Northern Research Ltd.
Box 3511 Station C
Ottawa, Canada K1Y4H7
(613) 596-2210

General Optronics Corp.
3005 Hadley Rd.
South Plainfield, NJ 07080
(201) 753-6700

Hewlett Packard
Opto-Electronics Div.
640 Page Mill Rd.
Palo Alto, CA 94304
(415) 493-1212

Laser Diode Labs Inc.
205 Forrest St.
Metuchen, NJ 08840
(201) 549-7700

Motorola Semiconductor
5005 E. McDowell Rd.
Phoenix, AZ 85008
(602) 244-6900

Plessy Optoelectronics
1641 Kaiser Ave.
Irvine, CA 92714
(714) 540-9934

RCA Corp.
New Holland Ave.
Lancaster, PA 17604
(717) 397-7661

Spectronics Inc.
830 E. Arapaho Rd.
Richardson, TX 85080
(214) 234-4271

Texas Instruments
Box 225012, MS 308
Dallas, TX 75265
(214) 238-4422

The cabling materials can be split into two groups: strength members (Table 5.3) and jacketing materials (Table 5.4). The particular requirements of the cable will determine the proper strength member to be chosen. Arimid is normally used. However, its negative coefficient of expansion creates problems during temperature cycling and can cause optical fiber failure. Arimid is easy to terminate to the connector. Silica, on the other hand, is hard to terminate as it is so brittle, but there are no temperature problems. Although arimid is easier to use, under conditions of extreme temperature cycling (as in full mil specs), silica strength members will probably need to be specified. Jacketing materials come in a wide variety. Abrasion resistance and flexibility are factors of the thickness of the jacketing chosen. For NASA use, the parameters of flame retardency, temperature range, and solvent resistance will be the most important. With these considerations, Halar or Kynar appear to be most suitable. A tight jacketing cable structure should be used as low temperature problems with the loose jacketing structure have been encountered.

The fibers thought most suitable for space applications are presented on Table 5.5. PCS fiber is the choice for all short to medium (<100m) length runs. Long length runs will be handled by graded index glass on glass fibers. Table 5.6 shows the properties of the various fiber types. PCS and graded index glass fibers were chosen on their superior performance under anticipated conditions.

Criteria for active device selection is based upon the requirements of MIL-M-38510 Class B for microcircuits (NASA Grade 2). Table 5.7 contains the source selections while Table 5.8 lists the detectors.

The projected applications for fiber optics in space are essentially four in number:

1. Short/Medium Length (<100m), High Speed (>50 MHz) Data Bus.
2. Short/Medium Length (<100m), Low Speed (<50 MHz) Point/Point Link.
3. Short/Medium Length (<100m), High Speed (>50 MHz) Point/Point Link.
4. Long Length (<100m), High Speed (>50 MHz) Point/Point Link.

Low speed systems can be driven by LEDs and detected by PIN diodes. High speed applications will require the high frequency characteristics of ILDs and APDs. Table 5.10 summarizes the component selection.

Proper connector selection will depend on the cable structure selected. Of the several varieties available, the best suited are those being produced by Amphenol and Hughes.

It should be noted that any of the vendors listed on Table 5.9 are capable of creating a space qualifiable component.

5.1.3 Trends

Fiber optics is a relatively new technology. As such, it demands that more development work be done. Experience with currently available components is showing where more work is needed. Suppliers are responding, especially as the state of technology increases, by providing more advanced and practical devices. What follows is a projection of the technology in 1985.

Sources will be much less expensive in the 1985 time frame as mass production is incorporated. The packaging will be more convenient, incorporating connectors directly to the diodes. The packages will become hermetic, allowing the diodes to work in harsher environments and improving their reliability. Limitations on operating temperatures will be expanded as packaging and chip fabrication are further refined. Lifetimes will be greatly expanded as the mechanisms affecting bulk degradation and facet erosion are more fully understood and solutions are developed. Figure 5.2 is a summary of the trends.

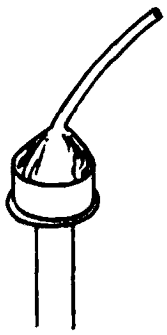
Connectors will also change as requirements are more fully developed. (See Figure 5.3.) Manufacturers are moving away from the use of adhesives in their connectors. The use of adhesives makes mounting very slow, especially in the field. Cleaving will replace polishing as the means of fiber end preparation, being quick and efficient.

TYPICAL APPLICATION			PRIMARY COMPONENT SELECTION			
TYPE	SPEED	LENGTH	SOURCE	DET	FIBER	COMMENTS
POINT TO POINT	<50MHz	<100M	LED	PIN	PCS	LOWEST IN COST AND CAPABILITY
POINT TO POINT	>50MHz	<100M	ILD	PIN	PCS	ILD REQUIRED FOR SPEED
DATA BUS	<50MHz	<100M	ILD	PIN	PCS	• ILD REQUIRED FOR POWER • NEEDS COUPLER DEVELOPMENT
POINT TO POINT	>50MHz	>100M	ILD	APD	GLASS ON GLASS	LONG LINE COMMUNICATIONS

TABLE 5.10 PRIMARY COMPONENT SELECTION

LED'S

1980

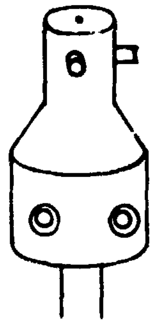


NON-HERMETIC PIGTAIL

10^5 HRS LIFETIME

0^0 TO 70^0 OPERATING RANGE

1985



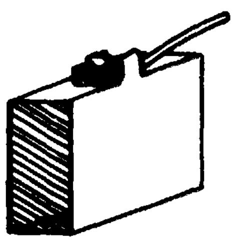
HERMETIC HOUSING INCORPORATING
A CONNECTOR

$>10^6$ HRS LIFETIME

-55^0 TO $+125^0$ C

COST $<$ 25% OF 1980

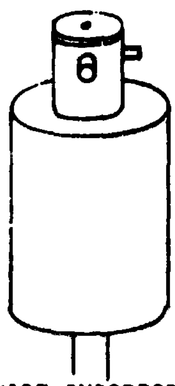
ILD'S



CHIP MOUNTED ON HEAT SINK

10^5 HRS LIFETIME

0^0 TO 70^0 OPERATING RANGE



HERMETIC PACKAGE INCORPORATING A CONNECTOR, CONTAINING COOLER REFERENCE DIODE, FEEDBACK AND DRIVE CIRCUITRY

10^6 HRS LIFETIME

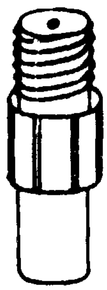
-55^0 TO $+125^0$
(WITH TEC'C COOLER)

COST $<$ 25% of 1980

FIGURE 5.2 FIBER OPTIC SOURCE TRENDS

SINGLE TERMINATION

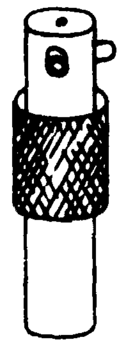
1980



THREADED

ADHESIVE LIMITATIONS
END POLISHING
NOT FIELD MOUNTABLE
TOO LARGE
EXPENSIVE

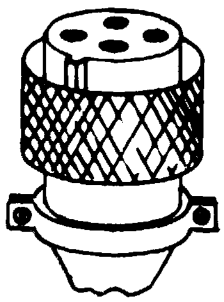
1985



BAYONET OR OTHER POSITIVE LOCK

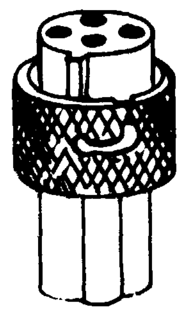
NO ADHESIVES USED
END CLEANED
FIELD MOUNTABLE
COST < 50% OF 1980

MULTI-TERMINAL



THREADED

ADHESIVES
END POLISHING
NOT FIELD MOUNTABLE
NO GANG TERMINATION
INADEQUATE STRAIN RELIEF
TOO LARGE
EXPENSIVE



BAYONET OR OTHER POSITIVE LOCK

NO ADHESIVES
END CLEANED
FIELD MOUNTABLE
SMALLER
GOOD STRAIN RELIEF
COST < 50% OF 1980

FIGURE 5.3 FIBER OPTIC CONNECTOR TRENDS

Multiport connectors will also become more practical. At present, they are merely several single terminals together in a single shell. Thus, the problems of termination are multiplied by the number of terminals. Also, strain relief is often neglected, making the connectors a likely place to damage the cables. Technical advances allowing gang termination and more emphasis on strain relief will improve the ease of use and reliability while reducing the cost of termination. As with all fiber optic components, standardization and an increase in use will lower the prices.

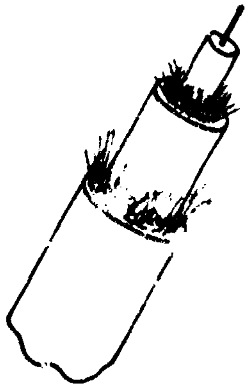
Fiber optic cables will improve more in performance over the next five years. Cable structures are many and varied, causing problems with the connector manufacturers. The establishment of requirements and the standardization of cables that fulfill them will aid the industry. Costs will drop as standard structures are mass produced. Figure 5.4 explains some of the trends in fiber optic fibers/ cables.

Optical fibers will continue to be refined; bandwidths are going to continue increasing and attenuation drop. More attention is being focused on radiation effects and work here will improve fiber resistance. The fiber itself will become more rugged, which will help improve its reliability and ease of termination. The use of single-mode fibers will increase.

Detectors are so well refined that major improvements in performance and reliability will probably not be forthcoming. However, as seen in Figure 5.5, packaging will become more practical, which will ease the use of fiber optics. Packages will be available already with ICs to improve high data rate performance, reduce noise, and simplify design requirements.

CABLES

1980



VARIED STRUCTURES

HIGH COST

PERFORMANCE LIMITED
(ESPECIALLY TEMPERATURE CYCLING)

1985

STANDARD STRUCTURES

COST 25% OF 1980

FULL MIL PERFORMANCE

FIBERS

HIGH COST

HIGH BANDWIDTH

LOW ATTENUATION

RADIATION SUSCEPTIBLE

FRAGILE

LIMITED TEMPERATURE RANGE
FOR PCS (-20 TO $+125^{\circ}$C)

COST 25% OF 1980

BANDWIDTH 10% HIGHER THAN 1980

ATTENUATION 20% LOWER THAN 1980

RADIATION RESISTANT

MORE RUGGED

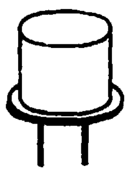
FULLER TEMPERATURE RANGE
(-70° TO $+180^{\circ}$C FOR PCS)

SINGLE MODE FIBERS AVAILABLE

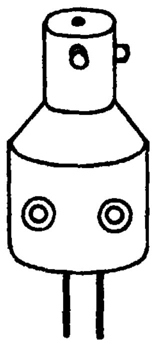
FIGURE 5.4 FIBER OPTIC CABLE TRENDS

DETECTORS

1980



1985



DETECTORS

CHIP MOUNTED BEHIND WINDOW
HERMETIC PACKAGE
HIGH PERFORMANCE
LOW COST
RUGGED

HERMETIC HOUSING
INCORPORATING CONNECTOR
AND ALSO IC
HIGH PERFORMANCE
LOW COST
RUGGED

FIGURE 5.5 FIBER OPTIC DETECTOR TRENDS

Transmitter and receiver modules will also reflect the advances made in other fields of fiber optics. The modules will have improved performance and be able to operate in a wider variety of environments. Modules incorporating ILDs and APDs will have been introduced. The wide variety of modules will ensure a proper solution to most design problems where modules would be considered. See Figure 5.6.

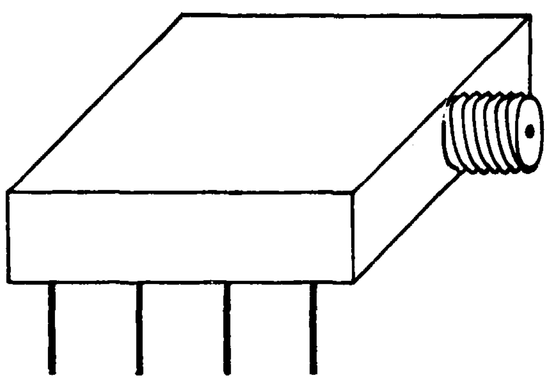
By 1985 a practical coupler will have been introduced. Several companies are working on the problem now. Compared to current couplers, the insertion losses will be much lower. The signal range will also tend to be lower. As current devices are still in a prototype configuration, the advanced couplers will be more rugged and, incorporating advances in multiterminal connectors, be much smaller. Prices will also drop to more acceptable levels with the increase in sales making more mass-production techniques applicable.

The establishment of testing standards and procedures will greatly stir test equipment development. Currently, most manufacturers build their own equipment which makes evaluation by the user difficult. Equipment will be available which will perform parametric analysis of devices. Field-use equipment will become more widespread and more accurate. Prices will need to drop in order to increase the use of equipment. At present, the only well developed piece of test equipment is the photometer.

Mention should be made of the use of higher wavelengths in fiber optics. As the attenuation of fibers drops at higher wavelengths, potential users see applications in very long run fiber optic links. Development work on sources and especially detectors is being pushed and by 1985 reliable devices should be available. The advantages in attenuation are really only felt on extremely long runs (over 10 Km) and they will probably be used mainly in specialty applications.

MODULES

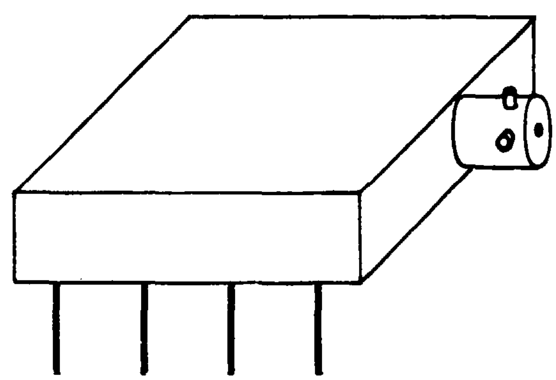
1980



NONHERMETIC

TEMPERATURE LIMITATIONS
LOW DATA RATES (TO 10 MB/S)
SMALL DYNAMIC RANGE

1985



HERMETIC

FULL MILITARY PERFORMANCE
HIGH DATA RATES (TO 50 MB/S)
DYNAMIC RANGE INCREASED BY 20dB
COST 50% OF 1980

FIGURE 5.6 FIBER OPTIC MODULE TRENDS

5.2 Standardization

The only released standards available today are DoD-STD-1678 on fiber/cable test methods and EIA RS440, a glossary of fiber optic terms. General specifications covering all major components are in work and should be out as drafts at the end of the year 1980. Detail specifications will follow shortly. Although there are no "qualified" parts, there are parts that could be qualified once desired characteristics and parameters are defined. NASA requirements for fiber optic components could be mirrored by participation in industry/government committees such as SAE, EIA, and the tri-services. See Figure 5.7.

5.3 Reliability

The major failure modes and mechanisms for the various fiber optic components have been identified and are tabluated on Table 5.11. Although the modes and mechanisms have been identified, methods to solve them have not necessarily been developed. In the case of sources, for example, the causes of some of the failure mechanisms are still undetermined. Cable problems are primarily material and structures related but cabling companies lack the resources to address all the problems.

In Section 4.0, the major failure modes and mechanisms are addressed in more detail under their respective components.

With the lack of reliability data available, it is hard to draw any conclusions. The major areas where reliability will be a problem is in fiber optic sources, connectors, and in the fiber/cable. The fiber/cable reliability problems are mainly due to material limitations and should be correctable with a directed effort to solve them. There are few mysteries as to the problems and high reliability cables will, no doubt, be developed.

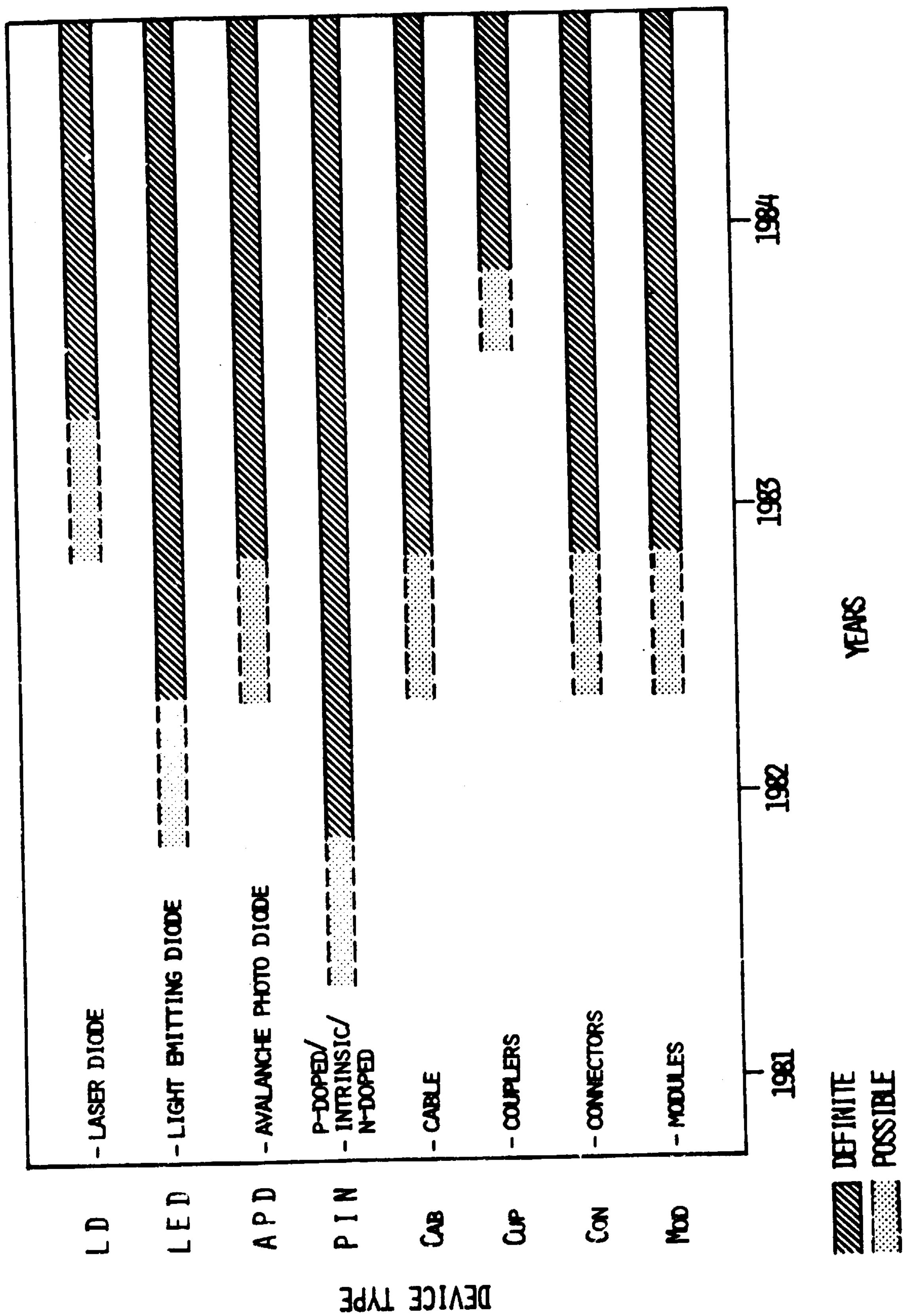


FIGURE 5.7 PREDICTION OF HIGH RELIABILITY PARTS

DEVICE	FAILURE MODES/PROBLEMS	RELIABILITY
INJECTION LASER DIODES (ILD)	INFANT MORTALITY FACET DAMAGE BULK DEGRADATION FACET EROSION	~1% / 1000 HOURS
LIGHT EMITTING DIODES (LED)	INFANT MORTALITY BULK DEGRADATION	~1% / 1000 HOURS
AVALANCHE PHOTODIODE (APD)	ELECTRICAL OVERSTRESS FABRICATION PROBLEMS	≈.1% / 1000 HOURS
PIN PHOTODIODE (PIN)	FABRICATION PROBLEMS	≈.1% / 1000 HOURS
CONNECTORS	MECHANICAL ABUSE CONTAMINATES (DIRT) WEAR	NO DATA
CABLE	FABRICATION PROBLEMS STRESS CORROSION	NO DATA
OPTICAL FIBERS	MECHANICAL STRESS RADIATION	NO DATA

TABLE 5.11 FAILURE MODES

The problems with sources are not quite so easy. Not all of the causes of the failure modes are fully understood. Also, the technology as a whole is not as firmly established as that of cables. Any reliability estimates available now are mainly guesses. Companies are aware of the lack of data to support their claims and reliability studies are underway at several plants. Certainly, within a year, more data will be available and an accurate assessment of the reliability of sources will be possible.

The reliability of connectors also needs more study. Not enough work on the performance of connectors under harsh environments has been carried out. The lifetimes of some of the components used in termination (such as adhesives and matching fluids) are not completely established. A lack of requirements is partly to blame as connector manufacturers have been concentrating on reducing coupling loss and in making their connectors compatible with the wide variety of cable structures available. The establishment of requirements will make it possible for connectors to be developed that incorporate good performance with a high degree of reliability.

Figure 5.8 is an estimate of when high reliability devices will be available.

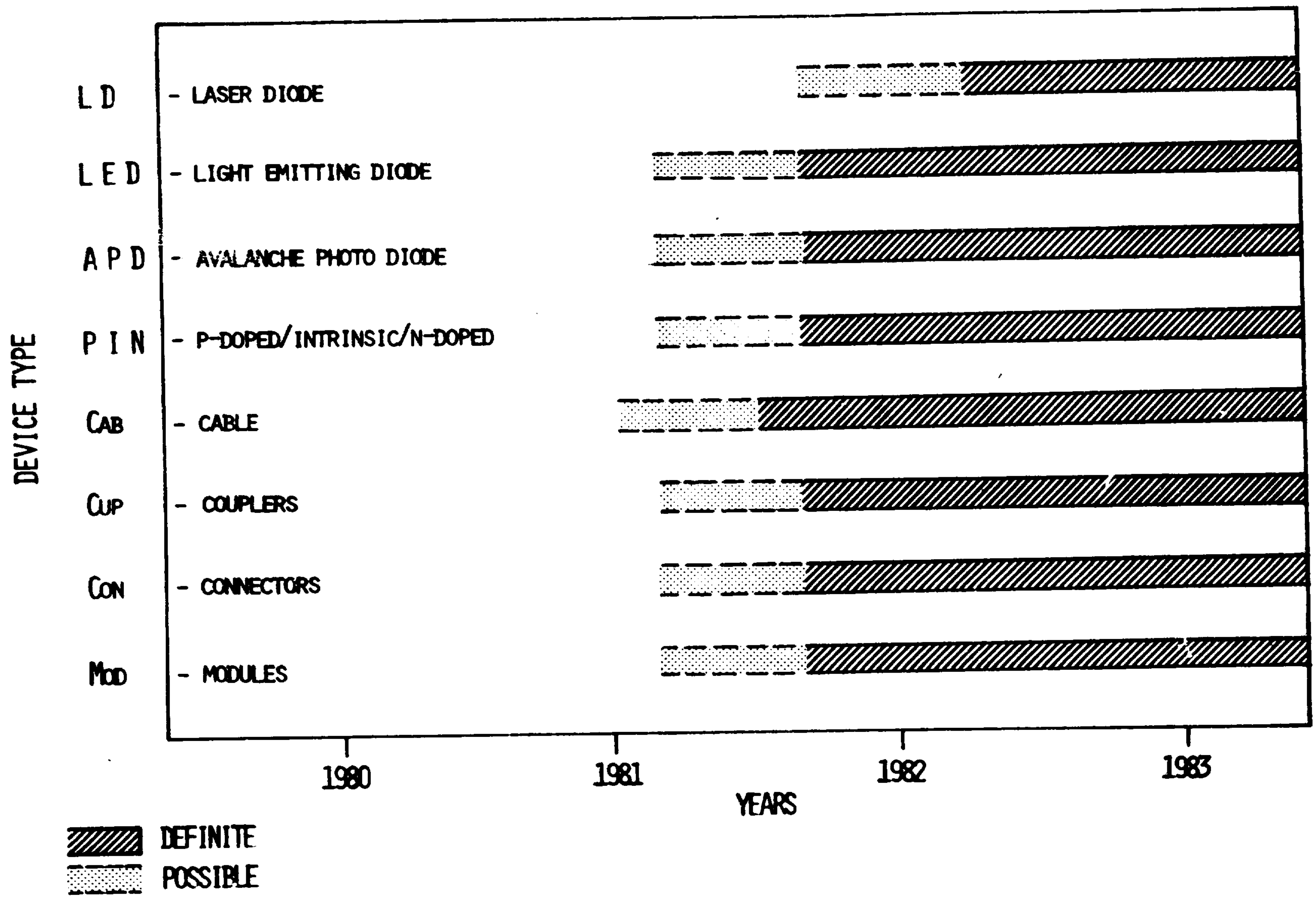


FIGURE 5.8 STANDARDS AVAILABILITY

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APPENDIX A

SAMPLE SURVEY FORMS

FIBER OPTIC SUPPLIER QUESTIONNAIRE

1) Fiber Optic Components Manufactured

Yearly Quantities

A. Sources
B. Detectors
C. Cable
D. Fiber
E. Connectors
F. Other: ____________________

2) Fiber Optic System/Assemblies Produced

Yearly Quantities

A. Couplers
B. Repeaters
C. Data Links
D. Systems
E. Other: ____________________

3) Do you use standards/specifications? _____No _____Yes

____Military
____Industry
____In-House

4) Do you use testing procedures or quality assurance programs to verify specifications?

_____Yes _____No

5) Have you encountered any significant problems with your testing program?

_____Yes _____No _____Not Applicable

6) Do you have any reliability data or pertinent information on failure?

_____Yes _____No

7) Which component/systems do you feel are suitable for standardization?

____

____

8) How many people are actively engaged in fiber optics or related activities at your facility(s)?

	Full Time	Part Time
A. Management		
B. Material		
C. Quality Assurance		
D. Engineering		
E. Technical		
F. Support		
G. Clerical		
H. Other		

9) Company Name: ______________________________

Principle Products: ______________________________

Number of Employees: ______________________________

Business Volume: ______________________________

Company Address: ______________________________

Telephone: ______________________________

10) Principle Contacts:

Management: ______________________________

Engineering: ______________________________

Quality Control: ______________________________

Material: ______________________________

FIBER OPTIC USER QUESTIONNAIRE COMPILATION

1) User Classification

___ Industrial
___ Military
___ Government Agency
___ Consumer

2) Applications

___ Communications
___ Control
___ Video
___ Data Transfer
___ Security

3) System Classification

___ Space
___ Aircraft
___ Ground Support
___ Marine
___ Computer Link
___ Telecommunications
___ CATV
___ Other: ____________________

4) Types of Components Purchased

	Quantity/Year	$ Value
A. Emitters		
B. Detectors		
C. Cable		
D Connectors		
E. Couplers		
F. Repeaters		
G. Data Links		
H. Installed Systems		
I. Other: ____________________		

5) Expected Growth Rate in $/Year

	80	81	82	83	84
A. Emitters					
B. Detectors					
C. Cable					
D. Connectors					
E. Couplers					
F. Repeaters					
G. Data Links					
H. Installed Systems					
I. Other: ____________________					

6) Do you use procurement or design standards/specifications for these items?

_____ No _____ Yes

_____ DoD
_____ Industry
_____ In-House

7) Do you use inspection or qualification testing to verify specifications?

_____ Yes _____ No

8) Do you use a maintenance program for servicing equipment in the field?

_____ Yes _____ No

9) Do you have reliability data or pertinent information on part failures?

_____ Yes _____ No

10) Have you encountered any testing problems?

_____ Yes _____ No

11) Have you encountered any installation problems?

_____ Yes _____ No

12) How many people are actively engaged in fiber optics or related activities at your facility(s)?

	Full Time	Part Time
A. Management		
B. Material		
C. Quality Assurance		
D. Engineering		
E. Technical		
F. Support		
G. Clerical		
H. Other: ____________		

13) Company Name: ____________
Principle Products: ____________
Number of Employees: ____________
Business Volume: ____________
Company Address: ____________
Telephone: ____________

14) Principle Contacts:

Management: ____________
Engineering: ____________
Quality Control: ____________
Material: ____________

TEST EQUIPMENT QUESTIONNAIRE COMPILATION

1) List test equipment you manufacture for fiber optics.

2) What is the reliability of the readings of your equipment?

3) Do you verify its reliability? _____ Yes _____ No

4) Which of your equipment is field usable?

5) Do you plan to adapt your equipment to field use? _____ Yes _____ No

6) Did you encounter any significant testing problems? _____ Yes _____ No

7) How many people are actively engaged in fiber optics or related activities at your facility(s)?

	Full Time	Part Time
A. Management		
B. Material		
C. Engineering		
D. Technical		
E. Quality Assurance		
F. Support		
G. Clerical		
H. Other		

8) Comapny Name: ______________________________

Principle Products: ______________________________

Number of Employees: ______________________________

Business Volume: ______________________________

Company Address: ______________________________

Telephone: __________ ______________________________

9) Principle Contacts:

Management: ______________________________

Engineering: ______________________________

Quality Control: ______________________________

Material: ______________________________